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CURRENTS AND POLLUTANT DISPERSION IN LAKE MICHIGAN, MODELED WITH EMPHASIS ON THE CALUMET REGION

by

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ABSTRACT

This report summarizes several years of Lake Michigan modeling efforts, with emphasis on recent, previously unpublished results and their implications for the preservation and improvement of nearshore water quality. These efforts, including the development of practical techniques for simulating large-scale circulation and dispersion, have illuminated some remaining technical problems and suggested ways for effectively modeling highly polluted regions like the Chicago-Calumet Harbor shoreline.

The use of hydrodynamic models in Great Lakes water-quality applications is briefly discussed, with special emphasis on pollutant-transport models and their use in studies of the fate of effluents discharged near shore in areas such as Calumet Harbor.

Previously reported Illinois-WRC-funded lake modeling efforts at UICC are reviewed. Computer graphics capabilities developed for effectively displaying model results and observations are described.

An adaptation of the Simons three-dimensional current model for Lake Michigan pollutant-dispersion studies is presented; the original model was verified extensively for Lake Ontario during the IFYGL effort. Typical results from the Lake Michigan version are presented to demonstrate its excellent capabilities for treating a wide range of large-scale phenomena.

A rationale is developed for the use of local episode simulations as a means of overcoming some difficulties in obtaining sufficient data for calibration and verification of whole-lake models. Then, following short descriptions of the Calumet Harbor region of Lake Michigan as a pollutant source and of the Chicago Department of Water and Sewers intake water-quality data for the Chicago shoreline, an application of a simple model to some observed "bad-water" episodes is presented. Comparison of observations and model results suggests that the onset of some periods of extreme pollution is governed by wind-driven transport. Such comparison also indicates that, under southerly wind conditions, high pollutant levels are often observed at the 68th St. Crib within 20-40 hours following a heavy rain at Calumet Harbor. The limitations of using a purely hydrodynamic model to treat bioreactive contaminants are shown, and improvements in resolution required in future, more accurate episode models are estimated. The use of models in analyzing complicated bad-water episodes is briefly investigated.

A number of conclusions are drawn regarding the directions in which future nearshore research efforts might profitably proceed.

Appendices describe some of the features desirable in an advanced nearshore model and present an evaluation of several existing three-dimensional models' potentials for nearshore applications.

Based upon the preliminary episode simulations performed, and upon the evaluation of the "state of the art" in Appendix B, a procedure is suggested for developing a useful multiple-grid-spacing version of the Simons model.

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KEYWORDS - computer model/water circulation/water pollution/dispersion/ lake currents/Lake Michigan/Calumet Region

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A NOTE ON AUTHORSHIP

As principal investigator bearing primary responsibility for these research grants, Dr. Katz is listed as the first author. The work herein, however, consists largely of research performed by Mr. Schwab in preparation for his submission of a Ph.D. proposal (Department of Information Engineering, UICC). Published works drawn from this research report list Mr. Schwab as the first author and Dr. Katz as the second author.

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INTRODUCTION

Rationale for Simulation Models of the Great Lakes

Preservation and improvement of Great Lakes water quality are vital to millions dependent upon these lakes for drinking water, commercial shipping, and recreational opportunities. In the future, increasingly complex water-quality management efforts will require detailed knowledge of the many consequences of existing and proposed effluent discharges and shoreline development. This knowledge will be difficult to obtain through direct observation alone, for such large systems as the Great Lakes; simulation models, once verified, will be able to contribute much insight into important limnological processes.

Hydrodynamic models are already in regular use for practical applications. Models (e.g., Paskausky and Murphy 1973, Haq, Lick, and Sheng 1974, Simons 1973b) can effectively predict shoreline flooding caused by storm surges. With the addition of fairly simple transport, decay, and sediment-interaction mechanisms, such models can predict large-scale motions of conservative (e.g., Lam and Simons 1974) and non-conservative (e.g., Lam, Jaquet, and Burns 1975) pollutants.

In important coastal boundary regions, models have been used to predict the behavior of heated discharges from power plants (e.g., Paddock, et al 1973) and (qualitatively) the effects of proposed changes in shoreline (e.g., Lick, Paul, and Sheng 1975); some thermal plume simulations have been verified to a limited extent.

Biological models for large lakes, still in an early stage of development, often show important characteristics of observations (e.g., Thomann, et al 1974); the needed improvement in these models seems more dependent upon the acquisition of sufficient data for large-scale verification than upon improvements in mathematical techniques.

A model which can be shown to represent important observed episodes effectively with a consistent treatment of parameters can be useful in predicting future episodes of interest, at least qualitatively. A realistic model can "fill in" gaps between measured data points much more effectively than less mechanistic interpolation and extrapolation schemes, thus displaying underlying phenomena more clearly.

Future, more advanced models, as are now under development, will provide much more information than those presently available, especially in the nearshore zones where man's activities have their first and greatest impact.

Development of Pollutant Dispersion Models

Because regulation of effluent discharges must be based upon understanding of their environmental consequences, studies of the dispersion of pollutants near their sources can have great practical value. The effectiveness of dispersion in quickly reducing concentrations near outfalls can vary greatly with changing weather conditions (Schwab and Katz 1974, 1975a, b, Katz and Schwab 1975, Murthy 1972). It seems desirable, therefore, to study "worst cases" of pollutant buildup (Schwab and Katz 1974, Katz and Schwab 1975). Regular observations of actual near-field dispersion, especially during storms when discharge levels might be expected to increase dramatically, would require major, intensive research efforts. The use of verified numerical models for currents and their associated dispersion to simulate hypothetical cases offers an attractive alternative for gaining insight into the immediate fate of materials discharged near shore.

In addition, detailed nearshore dispersion models can add considerable realism to chemical and biological water-quality simulations (e.g., Canale, et al 1973, Bierman 1975, Canale and Green 1972, Chen and Orlob 1972, Park, et al 1974) by treating large transient inputs which might be "missed" by using only average discharge values. Preliminary studies to be presented here indicate that, while conservative-pollutant models cannot realistically treat many important non-conservative materials, hydrodynamic dispersion mechanisms must be included in any spatially-detailed ecosystem models. One possible scheme for lake ecosystem modeling is shown in Figure 1; in this scheme, a wind-driven circulation model "drives" a purely hydrodynamic pollutant transport model which, in turn, drives and is driven by "local" biological models (with horizontal mixing assumed in each local region) for each area of special interest. Hydrodynamic transport models, then, may be thought of as necessary building blocks for broader water-quality simulations (Thomann, et al 1974).

Considerable insight can be obtained, also, by treating non-conservative substances as conservative for sufficiently short periods (about 1-3 days for NH_3 - N and coliform in Lake Michigan).

Since pollutant dispersion is dependent upon currents, but not vice versa, most dispersion models are based on circulation models. A wide range of useful circulation models have been developed, with widely varying degrees of complexity corresponding to the needs of specific practical applications.

The simplest circulation models (e.g., Reid and Bodine 1968, Leendertse 1970, Allender and Green 1975, Connor and Wang 1973) assume complete vertical mixing and compute only vertically-integrated water transports and surface motions; at best, such models would be useful in coarse-resolution ecosystem models of unstratified lakes (e.g., Lake Michigan in winter and spring). Such models can, however, predict water levels and total integrated transports economically (e.g., Paskausky and Murphy 1973). For simulations

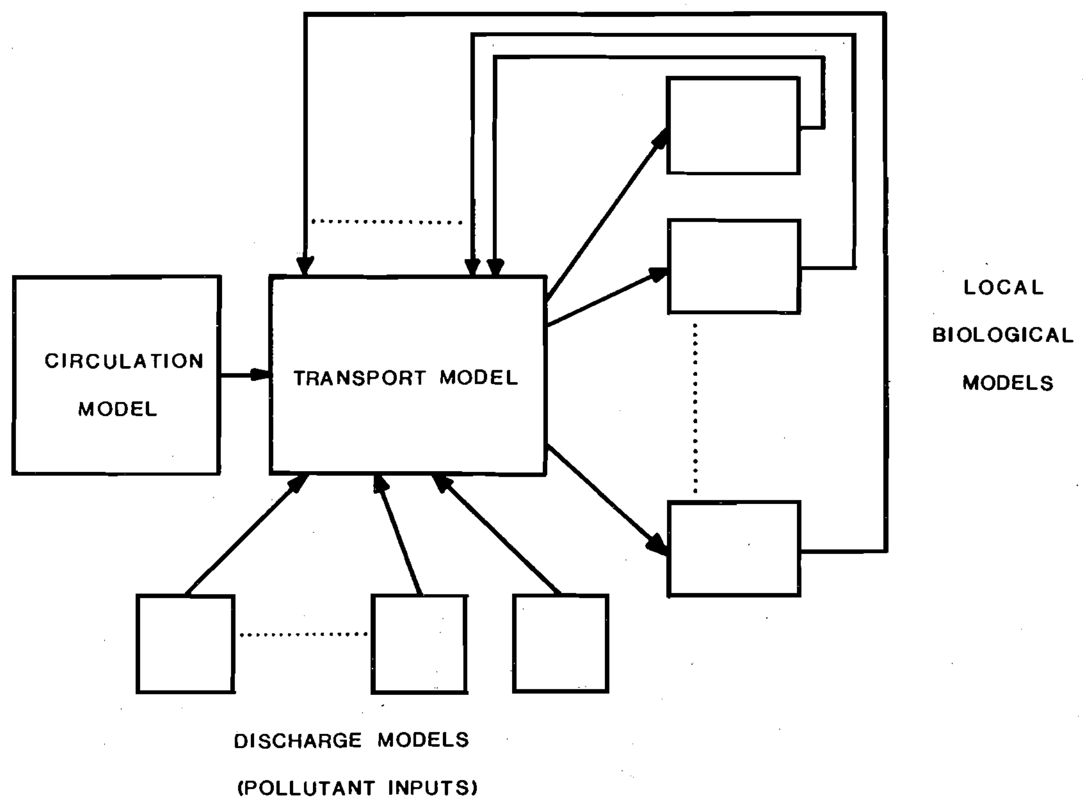


Figure 1. One possible scheme for a lake-wide ecosystem model.

requiring vertical resolution of circulations (e.g., Lake Michigan in summer), some form of three-dimensional model is necessary.

The simplest models for stratified summer flows consider two homogeneous layers separated by an impermeable, movable thermocline (e.g., Lee and Liggett 1970, Gedney, et al 1972, Kizlauskas and Katz 1973, 1974). In such models, vertically-integrated transports are determined separately for the epilimnion and hypolimnion; no material exchange between layers is allowed. The Kizlauskas-Katz 2-layer finite-difference model was used for some of the episode simulations to follow; its details are given in references (Kizlauskas and Katz 1973, 1974). Two-layer sealed-thermocline models could probably be used effectively in simulating transport processes in open lake waters; greater resolution is required to treat nearshore processes accurately.

Where greater vertical resolution is required, a model having more than two layers or levels separated by fixed, permeable interfaces (e.g., Simons 1972, 1973a, 1974, Bennett 1974b, Leendertse, et al 1973, Lick, Paul, and Sheng 1975) may be employed. Such models allow the computation of horizontal velocities at different depths, vertical velocities, and three-dimensional temperature distributions for use in treating baroclinic components of circulation. The Simons model, developed for use with data from the International Field Year for the Great Lakes (IFYGL), has been compared extensively with observations; this model has been adapted to Lake Michigan and a pollutant-dispersion mechanism added, as will be described in a later section. Those features desirable in a three-dimensional circulation model to be used for future multiple-grid-spacing nearshore applications are described in detail in Appendix A; several existing "state-of-the-art" models are discussed briefly in Appendix B.

Pollutant-dispersion models based upon circulations generated by existing models have been developed for many areas of interest, such as Lake Erie

(Lam and Simons 1974, Lam, Jaquet, and Burns 1975, Lick, Paul, and Sheng 1975, Sheng and Lick 1975), Lake Michigan (Schwab and Katz 1974, Katz and Schwab 1975), and Saginaw Bay (Richardson 1974, 1975).

In general, then, whole-lake circulation and transport models are fairly well developed for large-scale phenomena. Models for flows and dispersion in streams and estuaries are also well developed (e.g., Boericke and Hall 1974, Loziuk, et al 1972). In terms of hydrodynamic model development, the greatest present need is for nearshore models which could treat the transfer of pollutants from rivers, streams, harbors, and industrial outfalls to coastal regions and open lake waters. Verification of these models would necessarily require the acquisition of large amounts of observational data for limited regions of major importance, such as the Calumet Harbor-Chicago shoreline area of Lake Michigan. Frequent measurements of transient effects would be especially useful.

The next major section presents a brief review of previously reported Illinois WRC-funded circulation and dispersion modeling efforts at UICC and an introduction to the new material to be described in later sections. This section also includes a description of the computer graphics capabilities developed for displaying model results and observations effectively.

WRC-FUNDED LAKE MODELING EFFORTS AT UICC

Development of a Two-Dimensional Circulation Model

The Kizlauskas-Katz circulation model (Kizlauskas and Katz 1973, 1974, Katz and Schwab 1975) was developed as an efficient means of simulating large-scale wind-driven motions in Lake Michigan under strongly stratified or unstratified conditions. The model has a free surface at the air-water interface and includes the effects of rotation, bottom friction, and realistic bottom topography. Under unstratified conditions, the model has one layer in which vertically-integrated water transports are computed. Stratification is simulated by computing integrated transports in each of two layers separated by a sealed, movable thermocline. The use of only one or two layers, while ignoring details of velocity changes with depth, provides an effective means of treating movements of water mass at low computational expense. A 46 x 24 grid of 10.8 km squares was employed. As described in references (Kizlauskas and Katz 1973, 1974), the model's results agree generally with observations of coastal jet formation, thermocline displacement, free surface displacement, and velocity magnitudes, under a variety of wind forcings.

The computer program used to implement the model has been documented (Kizlauskas and Sapienza 1974) and is easily adapted to other lake or estuary geometries.

The Kizlauskas-Katz model has been used, in conjunction with the dispersion model described immediately below, in simulating hypothetical and observed episodes of pollutant motion.

Development of a Two-Dimensional Pollutant Dispersion Model

The integrated layer transports produced by the Kizlauskas-Katz model were used as input to a conservative-pollutant dispersion model developed to simulate large scale movement of contaminants in Lake Michigan. Since layer transports are used as input, a vertically-integrated (two-dimensional) diffusion-advection equation is solved for each layer, generating a depth-averaged concentration value for the center of each square grid cell. The mass-conservative explicit finite-difference formulation of this model is described in detail elsewhere (Schwab, Katz, and Belytschko 1974, Katz and Schwab 1975).

After initial testing, the two-dimensional dispersion model was applied to a hypothetical 125-day simulation of lakewide pollutant motion during the summer of 1970. U.S. Weather Service wind data and USEPA "STORET" chloride discharge data for 28 sources were used to provide a realistic situation (Schwab and Katz 1974, Katz and Schwab 1975). From this effort, it became obvious that such complex simulations were of severely limited value without great amounts of data for verification. As described in the section "Rationale for Episode Simulation" below, a technique was then proposed for obtaining much information of value while requiring relatively little data for verification (Schwab and Katz 1974, Katz and Schwab 1975).

The computer program used to implement the two-dimensional dispersion model has been documented (Schwab, Katz, and Yandel 1975a). This model is easily adaptable to other lake and estuary geometries and to using circulation inputs other than those provided by the Kizlauskas-Katz model.

New Work Presented in this Report

An adaptation of the Simons multi-layer three-dimensional model to the treatment of pollutant dispersion in Lake Michigan is described in the next major section. Some representative examples of the results obtainable are included.

The sections following the description of the modified Simons model deal with the development of a method of episode simulation and with a preliminary application of that method to some extreme cases of pollution seen in Chicago water intake data. Some of the material in these sections has been presented previously, at meetings of the Environmental Chemistry Division of the ACS (Philadelphia, April 1975) and the IAGLR (Albany, May 1975) (Schwab and Katz 1975a, b).

Computer Graphics Capabilities Developed

As part of lake modeling efforts at UICC, several specialized computer programs have been written for displaying circulation and pollutant-concentration patterns.

One program produces vector velocity (or transport) patterns, as shown in Figures 2, 3, and 6 of this report.

Another program produces contour plots of pollutant and velocity distributions; Figures 4, 5, 15, 16, 18, and 19 are pollutant-concentration plots produced in this manner. The contouring program is an adaptation of one developed in Canada for T.S. Murty (Taylor, Richards, and Halstead 1971).

Both plotting programs can be easily modified for other boundaries and locations of data points.

Output from either program can be displayed in two ways. After a data set representing a plot is generated by an IBM 370/158, a hard copy (India ink or ball point) can be obtained from that machine's Calcomp plotter. Alternatively, the data set can be transferred (via tape) to a PDP 11/45 minicomputer for diaplay on a Vector General CRT terminal. With the PDP-Vector General system, a number of plots can be stored on tape and quickly displayed in sequence, allowing the production of "moving pictures" on film or videotape.

THE SIMONS THREE-DIMENSIONAL MODEL

In developing a three-dimensional Lake Michigan model, it was decided that little advantage would be gained by "starting from scratch", given the existence of a number of verified models for other lakes (Appendix B). The model developed by T. J. Simons of the Canada Centre for Inland Waters has been compared extensively with Lake Ontario data, and has been shown to produce results in excellent general agreement with observations on that lake (Simons 1973b, 1974). Also, this model includes, or can be easily made to include most of the necessary features of lake dynamics for a wide variety of large and small-scale applications, while still retaining considerable computational efficiency (Appendix B, Simons 1972, 1973a).

As applied here to Lake Michigan, the Simons model has a 10.8 km horizontal grid spacing and four layers in the vertical; the internal layer boundaries, for demonstration purposes, were set (nominally) at 10, 20, and 40 meters below the undisturbed free surface (actual depths were used where a layer intersects the bottom). The horizontal grid and bottom topography were essentially those used in the earlier Kizlauskas-Katz model (Kizlauskas and Katz 1973, 1974), partly for purposes of comparison. Within each layer, vector mass transports are computed at each corner of each cell and temperatures and surface displacements are computed for cell centers (as viewed from above). A three-minute time-step was used for free-surface computations, with a thirty-minute time step for all other calculations (see Appendix B), in the tests performed. In a number of tests using steady wind forcing, the results obtained appeared consistent with those obtained using the earlier model and with the observed behavior of the lake; strong coastal jets were seen in these tests for winds with strong longshore components.

Figures 2 through 5 are typical results from the Simons model; these results correspond to a hypothetical simulation of currents for August 3-16, 1972, using winds measured by the U.S. Weather Service at Midway Airport, Chicago to drive the entire lake. This period of rapidly changing winds was chosen to represent a typical episode in which pollutants discharged into Calumet Harbor would be "trapped" near their sources due to relatively ineffective wind-driven dispersion (a "worst case" as defined in the next section). Daily wind-speed and direction values were used for the 14-day simulation. Starting from the top, initial layer temperatures were set at 12.2, 11.1, 4.4, and 4.4 degrees C, respectively, corresponding to average August values ("The Lake Michigan Basin", 1975); currents and pollutant concentrations were initially assumed to be zero, and a continuous, arbitrary conservative-pollutant discharge of 5,000g/sec (roughly the level of a large chloride source (Katz and Schwab 1975)) was established at Calumet Harbor on August 3 in the model. Vertical and horizontal eddy diffusivities were set at 100 and $10^6 cm^2/sec$, respectively.

Figures 2a and 2b show top-layer velocity patterns for August 9 and August 16, respectively. Figures 3a and 3b show bottom-layer velocities for the same two dates, respectively. Figures 4a and 4b show simulated top-layer pollutant contours for August 9 and 16, respectively, and Figures 5a and 5b show such contours for Layer 3 (at approximately 30m depth) for the same dates. As shown, most of the pollutant introduced remained in the southern tip of the lake because, under changing winds, no strong, steady currents developed to flush the area. Figures 6a and 6b show cross-sectional velocities for a vertical east-west section through Calumet Harbor on August 9 and 16, respectively.

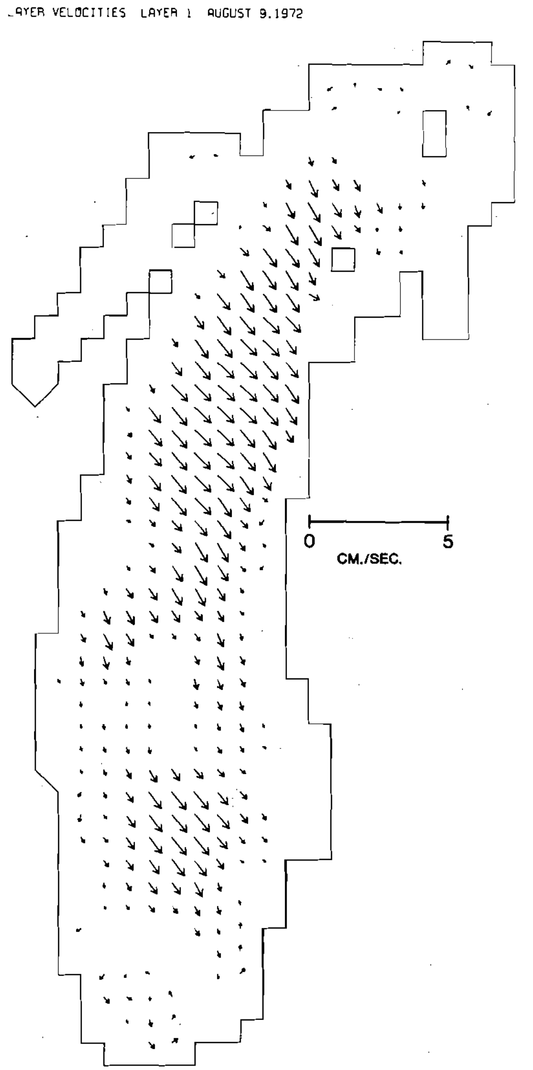


Figure 2a. Simons model results: computed top-layer (Layer 1) velocities for August 9, 1972.

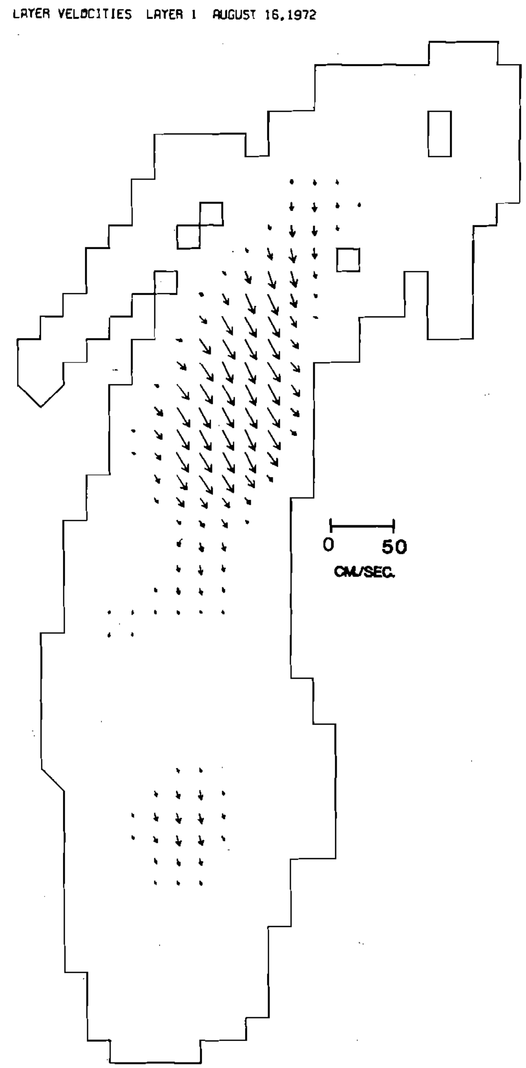


Figure 2b. Same as Figure 2a, but for August 16, 1972.

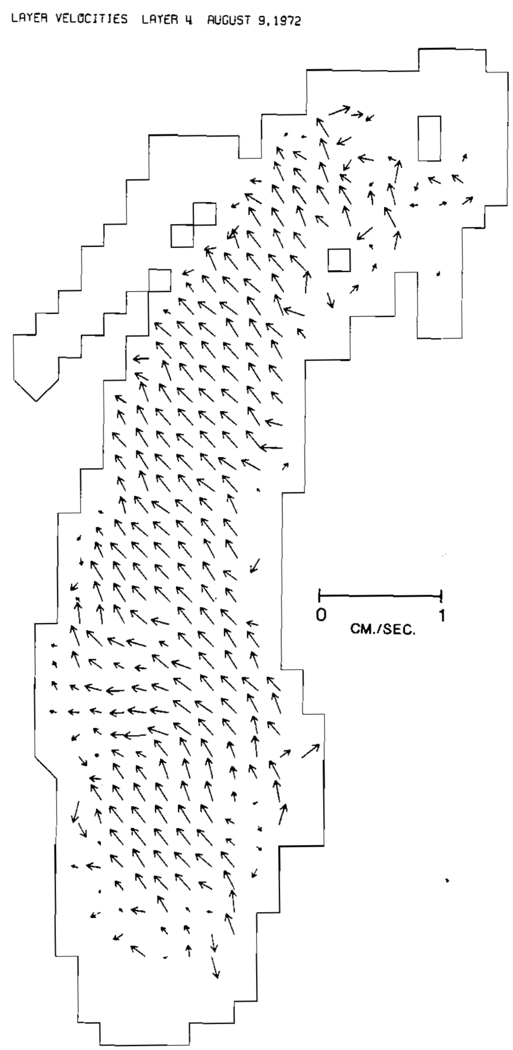


Figure 3a. Simons model results: computed bottom-layer (Layer 4) velocities for August 9, 1972.

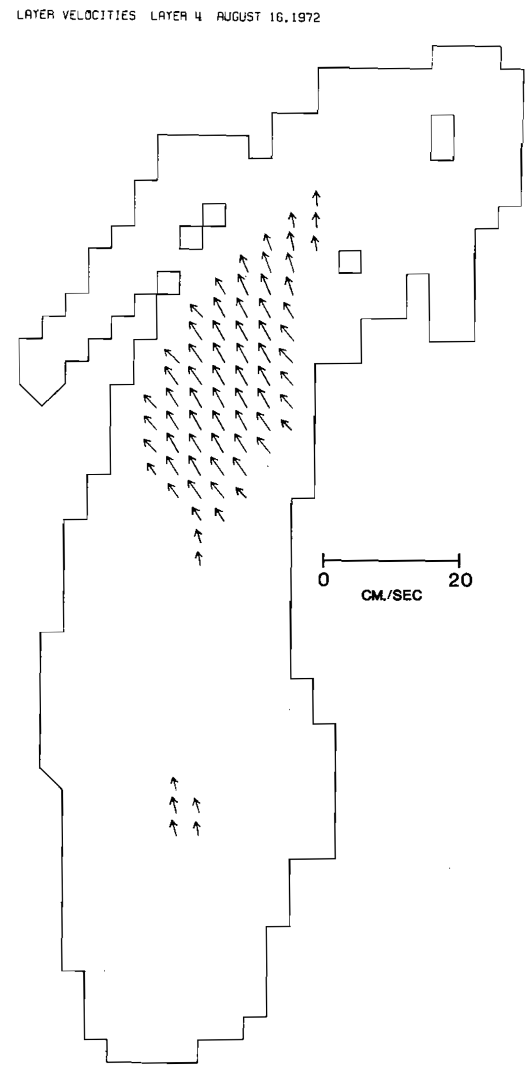


Figure 3b. Same as Figure 3a, but for August 16, 1972.

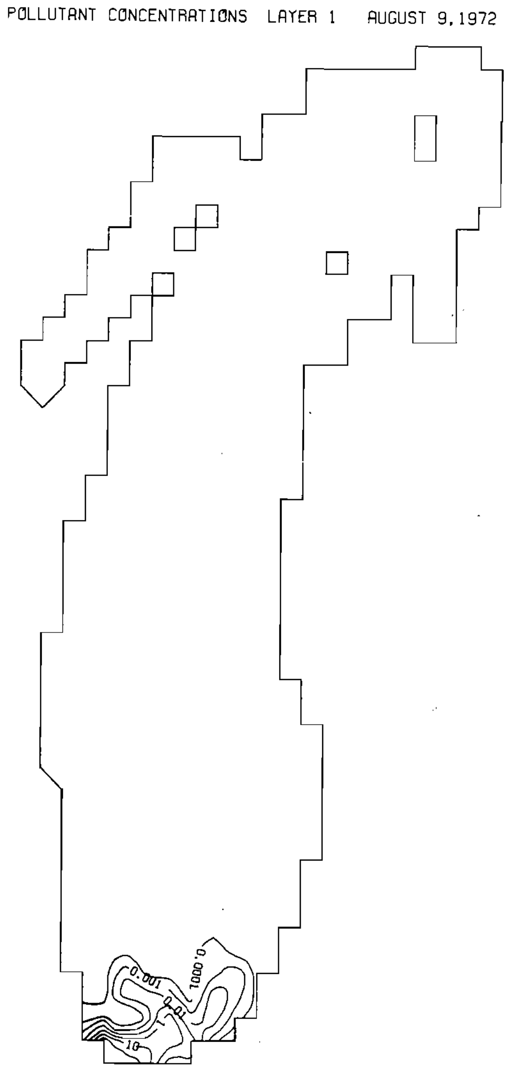


Figure 4a. Simons model results: simulated top-layer (Layer 1) pollutant concentration contours for August 9, 1972 (units of $10^{-9}g/cm^3$).

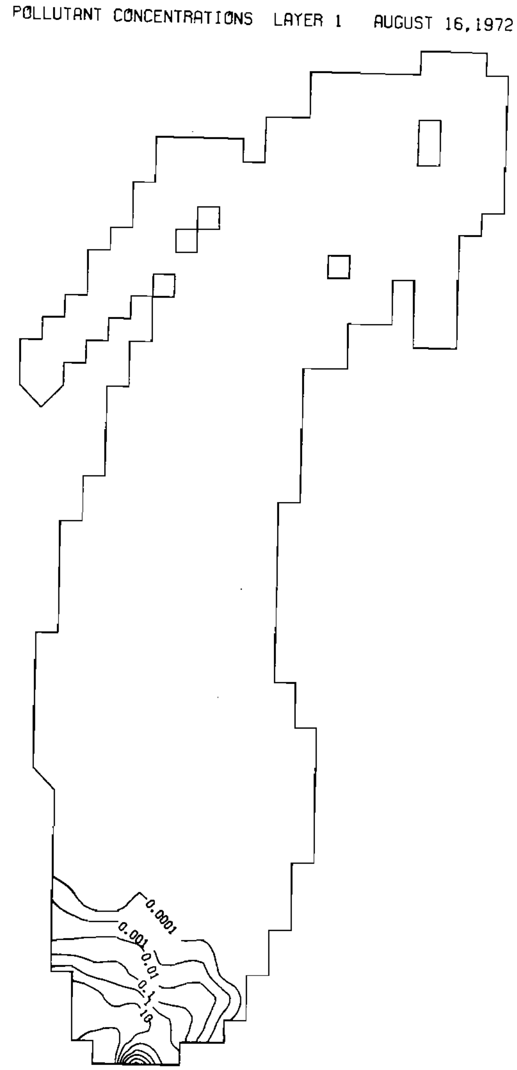


Figure 4b. Same as Figure 4a, but for August 16, 1972.

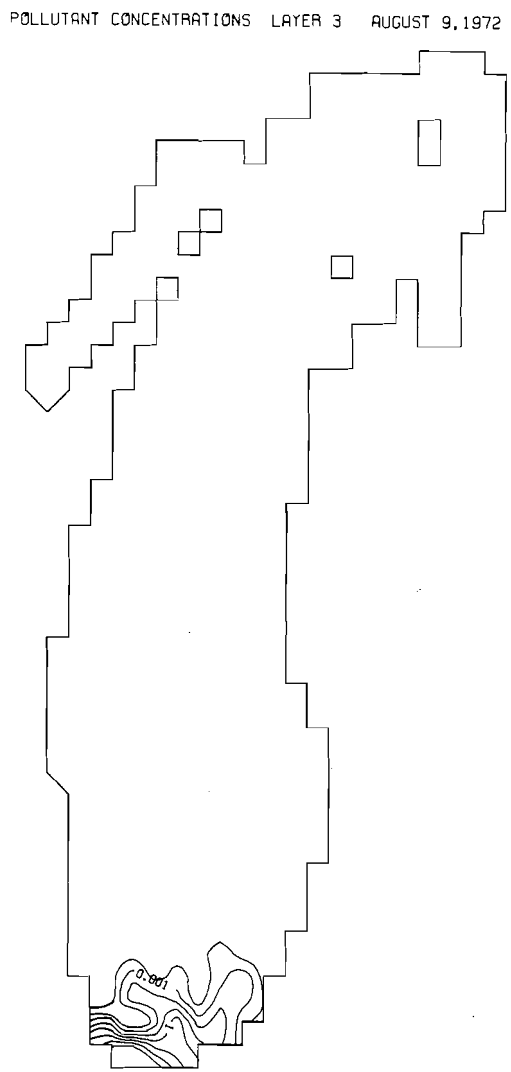


Figure 5a. Simons model results: simulated Layer 3 (30m depth) pollutant concentration contours for August 9, 1972 (units of $10^{-9} g/cm^3$).

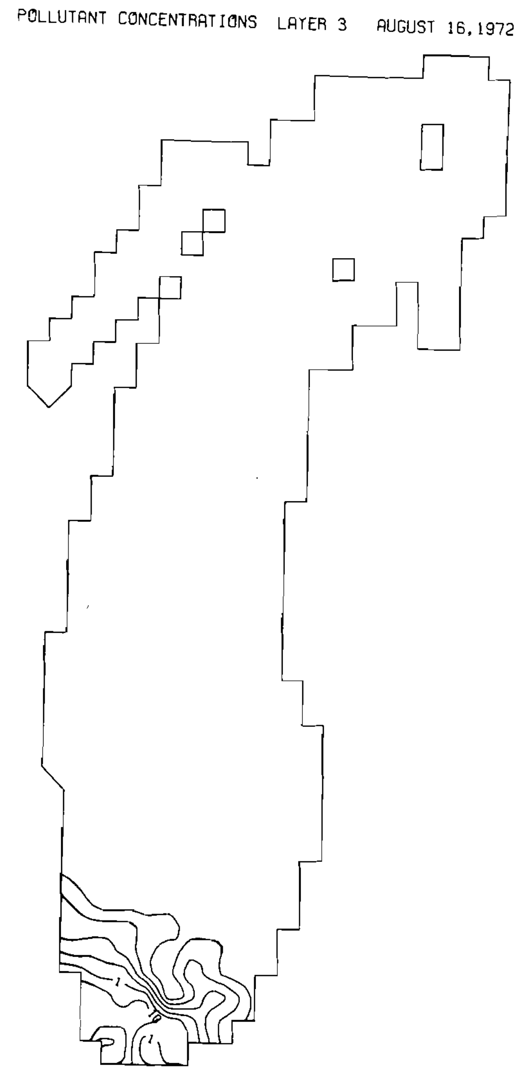
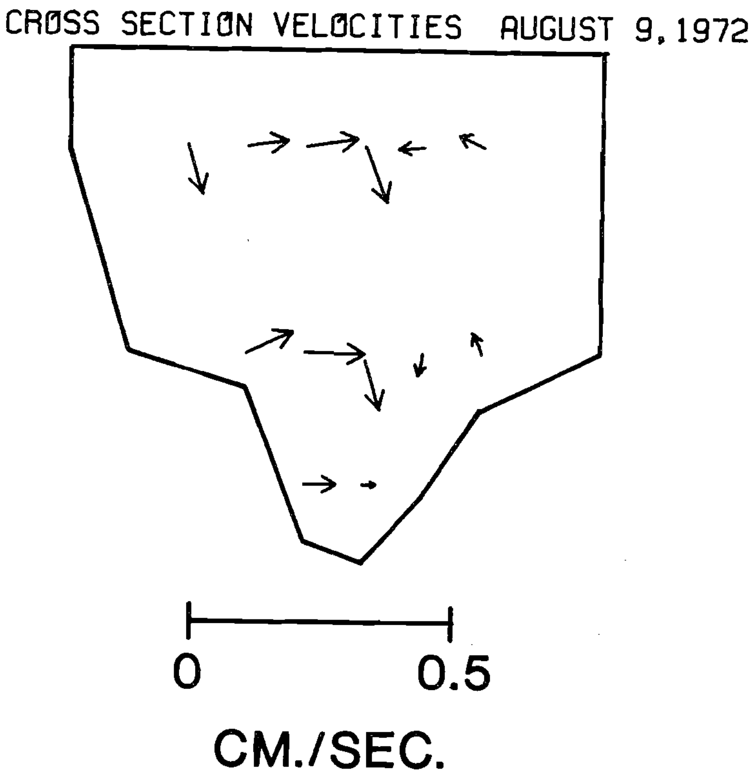


Figure 5b. Same as Figure 5a, but for August 16, 1972.



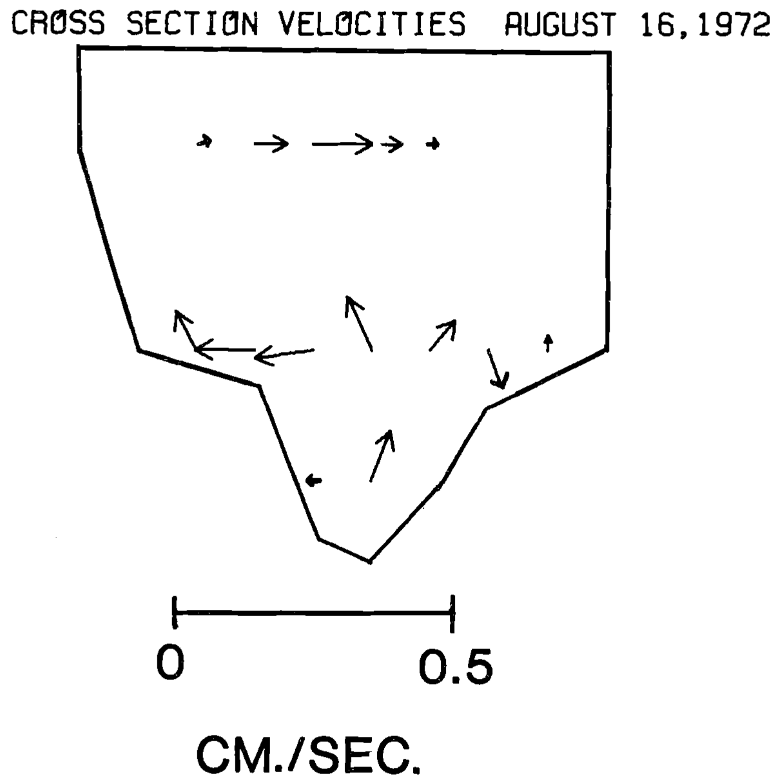


Figure 6a. Simons model results: computed cross-sectional velocities for August 9, 1972, for an east-west section through Calumet Harbor, as viewed from the south.

Figure 6b. Same as Figure 6a, but for August 16, 1972.

The arbitrary demonstration case shown cannot, of course, be thought of as representing actual lake conditions, although the seven simulated days elapsing before currents are shown and the probable unimportance of background pollutant concentrations (Schwab and Katz 1975a, b) reduce the importance of realistic initial conditions in this case. These results are presented simply as a brief illutstration of model capabilities. For comparisons of model results with actual observations of Lake Ontario, see Simons (1973b, 1974). Obtaining sufficient weather and initial temperature data for an actual realistic simulation of whole-lake currents would require an IFYGL-like effort on Lake Michigan. Only local data might be required for simulating important local phenomena. Such simulations will be described in following sections; the Simons model is expected to be used as the foundation for a multiple-grid nearshore episode model in the near future. The large-grid-spacing model is ready for direct applications to whole-lake problems of Lake Michigan at present, however.

The FORTRAN code for the modified Simons model has been fully documented (Schwab, Katz, and Yandel 1975b).

RATIONALE FOR EPISODE SIMULATION

One important question to be answered in the development of any ecosystem model for part of a large body of water is whether pollutant levels and sources well outside the immediate area considered need be described in detail. This question may be approached by considering individual sources in and around an area of interest one at a time and estimating the relative importance of each by introducing arbitrary discharges in the model.

In a number of such tests using the 2-layer model, considering many of the important streams and rivers discharging into Lake Michigan, it was apparent that pollutants, at least in the model used, were seldom transported very far from their sources without being greatly diluted. The nearshore velocities, either as observed in an actual lake (Csanady 1967, Snow 1974) or as generated by the model, were insufficient to rapidly flush pollutants away from their sources. In practice, several weeks were required for a slug of conservative pollutant to be almost completely transported from its point of discharge under realistic wind conditions. Because of its importance, the Chicago-Calumet Harbor shoreline was given special consideration in these tests.

For the Chicago area, the largest single pollution source is the Calumet Harbor region (Snow 1974). To determine what factors might necessarily be included in a model of transport from this region, single-slug discharges were simulated under a variety of wind conditions (Katz and Schwab 1975). In these simulations, arbitrary slugs of a conservative pollutant were introduced into the model at Calumet Harbor, and their behavior was observed for over thirty days. It was observed that, under "best case" wind conditions (essentially steady winds), these slugs were dispersed over a large area of the lake within a few weeks. Under "worst case" variable wind coneitions, the slugs tended to stay near their point of discharge for long periods (over thirty days) without dispersing greatly.

The best-and-worst-case results indicated that pollutants discharged near shore could behave in either of two ways after their release: they could disperse fairly uniformly and be greatly diluted before affecting areas a substantial distance away, or they could remain concentrated near their sources, causing large, unusual buildups analogous to those observed in the atmosphere during periods of thermal inversion. In either case, the major short-term effects of such pollutants seemed to be confined to the areas near their sources. The local velocities in the model were sufficiently small to rule out the possibility of pollutants being carried into the area from other regions before being greatly diluted. The concentrations produced by discharges outside the Calumet region considered would, therefore, probably be small in comparison with those produced by storm discharges into Calumet Harbor under extreme conditions. Thus, the authors felt that initial levels and discharges outside the region considered could reasonably be neglected in simulating short-term extreme cases of pollutant buildup (lasting, say, less than one week) resulting from such storm discharges.

The Chicago shoreline area appeared especially vulnerable to "worst-case" pollutant buildups because it is near the sources in the heavily-polluted Calumet Harbor area and because of the predominance of strong longshore coastal currents (in the direction of the longshore components of the wind) in the area. The model indicated that, under southerly or southwesterly winds, pollutants from Calumet Harbor could quickly reach Chicago beaches and water intakes and remain there during subsequent periods of changeable winds, possibly causing beach closings due to such things as high coliform counts, algae blooms or alewife die-offs and also causing water-treatment problems.

A search of the excellent data maintained by the Chicago Department of Water and Sewers revealed that episodes of "bad water", as indicated by sharp increases in ammonia-nitrogen and bacterial counts and by strong septic or hydrocarbon odors, did occur several times each year at the 68th St. Crib water intake. Many of these episodes coincided with periods of southerly winds following heavy rains which might have caused combined sewer overflows near Calumet Harbor. In the intervals between the episodes observed, the pollutants measured were all at low, fairly constant "background" levels near the threshold of detectability, consistent with the model's indication that initial conditions are of relatively little importance, in the lake itself, for these episodes.

Ammonia-nitrogen and coliform, two indicators measured routinely by the City of Chicago at its filtration plants, decay fairly quickly in lake water (Sawyer and McCarty 1967, Canale and Green 1972, Snow 1974); these indicators can decrease drastically in a few days even without dispersion. By comparison, model experiments on transport alone (conservative pollutant), in which the velocities involved were well within the range observed (Csanady 1967, Snow 1974), indicated that a slug of pollutant would require at least a week or two to be flushed from Calumet Harbor. Therefore it seems reasonable to assume that ammonia-nitrogen and coliform decay before traveling very far, so that these pollutants will show large concentrations only near their sources. Correspondingly, distant sources (i.e., sources more than 40-50km away) can probably be ignored due to decay (in addition to the effect of dilution described earlier) in simulating these pollutants in small areas such as the Chicago-Calumet Harbor region.

Because of the apparent unimportance of initial pollutant concentrations and distant sources in the Chicago shoreline area, the authors felt that a great deal could be learned about episodes gleaned from water intake data (in particular, those episodes not confounded by pollutants from disturbed sediments) if a single, very short slug were introduced into an initially clean (model) lake. This simplified simulation, based only on knowledge of the rainfall history (to estimate the timing of combined sewer overflows) and the wind history (to drive the circulation model after the discharge) would (1) give insight into the immediate fate of effluent discharges, (2) indicate the importance of including wind-driven transport in any whole-lake or shoreline region ecosystem models of water quality episodes, and (3) indicate the direction future modeling efforts should take.

THE CALUMET HARBOR REGION OF LAKE MICHIGAN AS AN EFFLUENT SOURCE

The Calumet Harbor region is the largest pollutant source, for many significant materials, in Lake Michigan. Its surrounding waters, upon which many large municipalities rely for drinking water, are the most eutrophic part of the lake. Snow (1974) presented a fairly thorough discussion of the effluent discharges in the area and the average water quality observed there. This report also presented a qualitative description of the general hydrology of the region, but did not treat the transient dynamic behavior of the area in any quantitative sense; this transient behavior seems to be of predominant importance, as will be shown. Much of the descriptive material in this section was taken from Snow's work.

The geography of the area is as shown in Figure 7. Note that the harbor is partially enclosed by a breakwater, and note the proximity of the Chicago South Filtration Plant water intake crib (68th Street).

The Indiana Harbor Canal flows continuously into the harbor; the flow in this waterway consists mostly of waste water from industry and sewage-treatment facilities. Under certain conditions, such as combined sewers overflowing, this canal can discharge unusually large amounts of effluent to the harbor. A large, black plume can usually be seen at the mouth of the canal; Figure 8 shows a typical discharge.

The Calumet River normally flows away from the lake, but its direction may briefly be reversed by large industrial discharges upstream from its mouth; industrial discharges near the mouth may, in part, enter the harbor directly.

Some industrial discharges are made directly into the harbor, as well.

A wide range of important pollutants are found in significant concentrations in Calumet Harbor. Contaminants discussed by Snow (1974) include

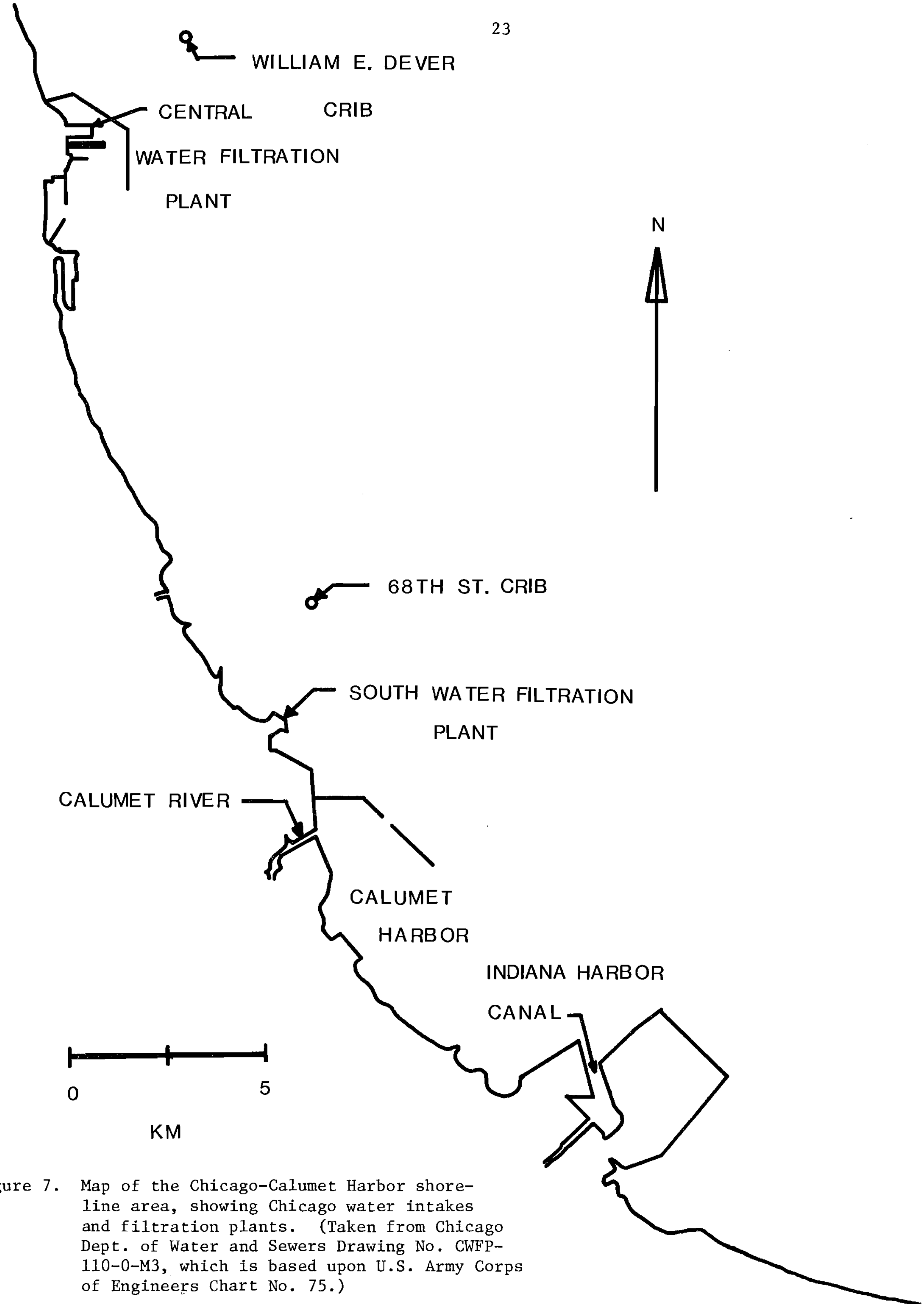


Figure 7. Map of the Chicago-Calumet Harbor shoreline area, showing Chicago water intakes and filtration plants. (Taken from Chicago Dept. of Water and Sewers Drawing No. CWFP-110-0-M3, which is based upon U.S. Army Corps of Engineers Chart No. 75.)

Figure 8. An aerial thermal infrared photograph of the Indiana Harbor Canal discharge, taken in 1974. (Photo courtesy of Phil Reed.)

ammonia-nitrogen, coliforms, phosphorous, phenols, oil, grease, chlorides, and sulfates. In addition to these, significant levels of highly toxic and long-lived trace contaminants (e.g., lead and other heavy metals) are present (e.g., Cogley 1974, Winchester and Nifong 1971).

Observations and computer simulations of currents in the Calumet Harbor area indicate clearly that nearshore currents tend to follow the shore, in the direction of longshore wind components. Under southerly winds, material discharged into the harbor would clearly move toward the Chicago shoreline.

THE WATER QUALITY RECORDS OF THE CHICAGO DEPARTMENT OF WATER AND SEWERS

The Chicago Department of Water and Sewers routinely monitors the quality of the water present at its four water intakes. The parameters measured are those most important to filtration plant operation, including ammonia-nitrogen, total bacteria, total coliform, fecal coliform, turbidity, temperature, pH, wind speed, and odor; none of the pollutants measured are conservative.

The Chicago water system has two large filtration plants: The Central Plant and the South Plant. Each plant has a shore intake and a crib intake; the locations of these intakes are as shown in Figure 7. The William E. Dever Crib supplies the Central Plant, and the 68th St. Crib supplies the South Plant. In general, the data from the shore intakes tend to show mainly effects from currents and sediments in their immediate vicinity, while the crib data show conditions fairly well out into the open lake. Since the model applied here did not attempt to represent detailed nearshore processes, only crib data were considered.

The parameters listed above are measured every four hours under normal circumstances; in addition, if very large values are noted, measurements are often taken more frequently until normal levels return.

A thorough search of Water Department data for the years 1970-1974 revealed that water at the cribs was generally quite clean for most of each year, with the measured pollutants all remaining at low "background" levels. At the 68th St. Crib intake of the South Plant, however, several episodes of "bad water" were noted each year. During these episodes, high levels of all measured pollutants were observed for periods of from one to about thirty days in length. Many of these episodes occurred shortly after storms, as determined from U.S. Weather Service data, during periods in which Calumet Harbor discharges would be expected to reach Chicago under the influence of southerly winds. Other episodes occurred simultaneously with storms and were thought to have resulted from sediments being disturbed. The longest episodes appear to have resulted from combinations of repeated single-slug discharges and/or sediment disturbances. Figures 9-11 illustrate a variety of typical "bad-water" episodes observed. Figure 9 shows measured $NH_3 - N$, coliform, turbidity, and wind direction for an apparent single-slug episode in June 1974; this episode will be discussed in greater detail in the next section. Figure 10 shows $NH_3 - N$ levels, rainfall, and wind direction for a short, but seemingly more complex episode in April 1974; the large peak on the third day (4/11) seems to correspond to a local sediment disturbance superimposed on the results of a storm discharge on or about April 10. Figure 11 shows $NH_3 - N$, rainfall, and wind direction for a long and complex episode in December 1972-January 1973; this episode will also be discussed in the next section.

In none of the episodes seen were large concentrations observed at the Central Plant following their observation at the South Plant.

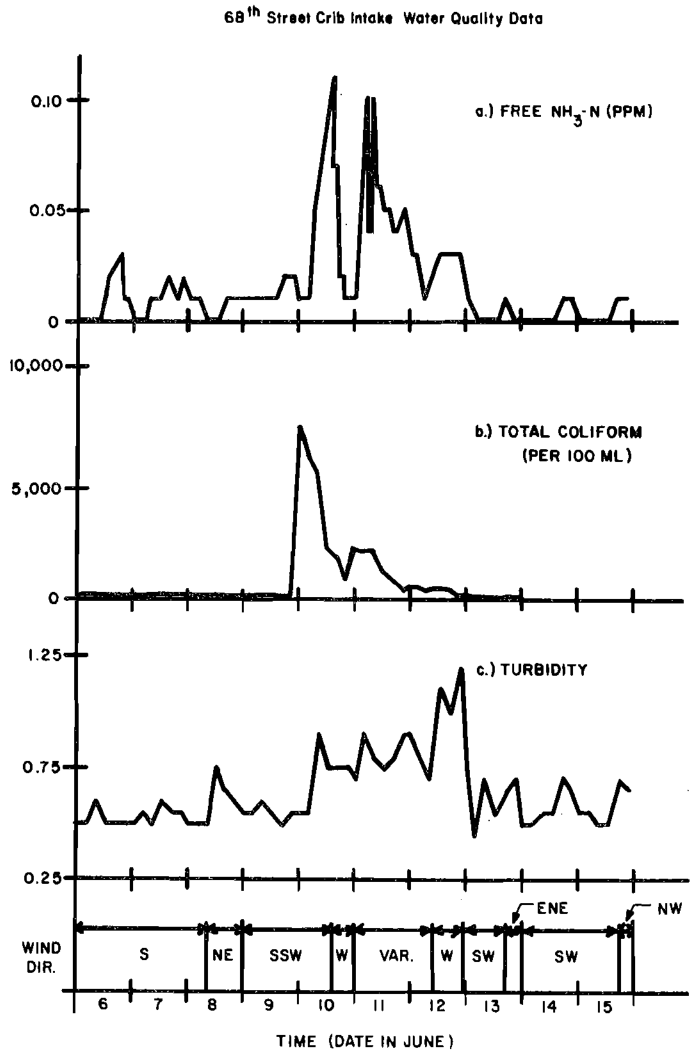


Figure 9. Observed ammonia, coliform, turbidity, and wind direction for an episode in June, 1974.

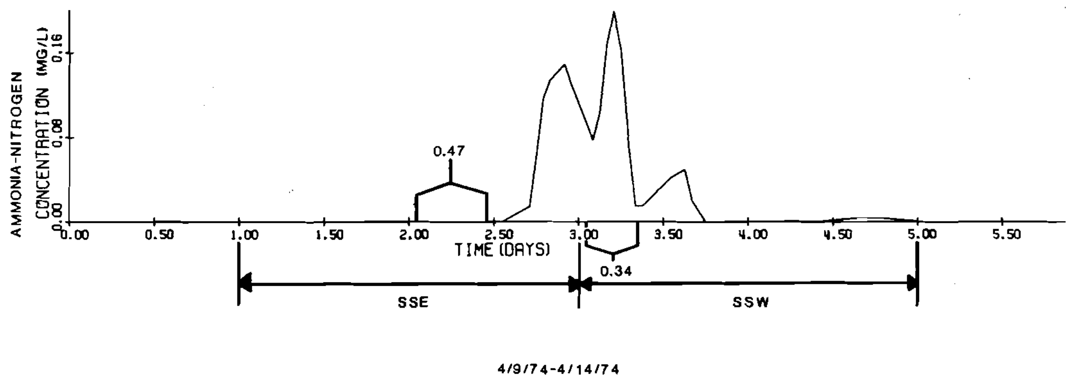


Figure 10. Observed NH_3-N levels, rainfall (numbers at brackets, in inches), and wind direction for an episode in April, 1974.

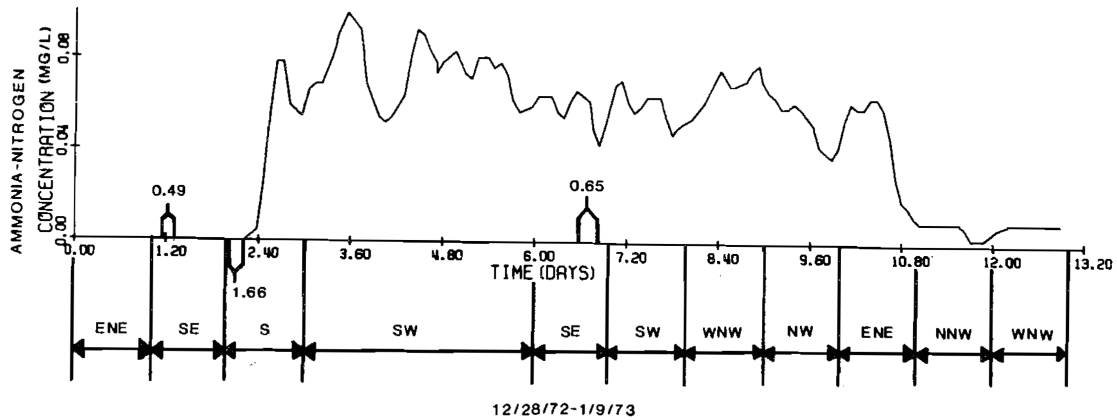


Figure 11. Observed NH_3 - N levels, rainfall (numbers at brackets, in inches), and wind direction for an episode in December, 1972 - January, 1973.

A SIMPLE MODEL APPLIED TO THREE OBSERVED EPISODES

Model Description

The two-dimensional whole-lake dispersion model used earlier in a search for hypothetical best and worst cases was applied directly to three extreme cases actually recorded at the 68th St. Crib. This model, while lacking sufficient spatial and temporal resolution to simulate finer details of observed episodes, was thought, because of the reasonable transport magnitudes and directions it produced, to offer a convenient and economical (in terms of computational effort) tool for first investigating the gross features of pollutant dispersion in the region considered.

The model employed used sequences of quasi-steady-state circulations generated by the Kizlauskas-Katz circulation model described above to approximate actual time-varying circulations. The resulting crude step approximation was employed as a means of greatly reducing the computer time required; the steady-state circulations for sixteen "standard" 3.8m/sec winds (N, NNE, NE, ENE, etc.) were generated beforehand and stored. These standard winds were fitted to the actual winds observed at the South Filtration Plant as described in detail in a previous paper (Schwab and Katz 1974). Because the circulation model required about one to two days of simulation to effectively approach a steady state, constant-wind approximation periods of less than about 24 hours would have been grossly inaccurate when used in a step approximation; the temporal resolution of the combined circulation-dispersion model was thus limited by the circulation model to events taking longer than about a day, even though the time step used for the dispersion model was much shorter. The step approximation used represents circulation patterns poorly during periods of changing winds and removes the effects of wave motions, except as these motions increase apparent diffusion. Actual currents in the region, however, have been observed (Snow 1974) to change direction so as to follow the longshore components of local wind stresses within a few hours after a change in wind direction. The overall water and pollutant transports resulting from such an approximation are probably realistic, except for fine details; savings in computer time are dramatic.

Figures 12 and 13 are typical top-layer steady-state velocity distributions generated by the circulation model. They show circulations for south and west winds, respectively.

The region of greatest interest here has a maximum depth of about 12m; the 68th St. Crib intake is at about 9m depth. The model had an equilibrium thermocline depth of 16.8m (Kizlauskas and Katz 1973, 1974) corresponding to observations (FWPCA 1967) and maximum thermocline displacements of approximately 6m (Kizlauskas and Katz 1973, 1974) in that region for a 3.8m/sec wind. Thus, the minimum thermocline depth was about 11m for the area considered, and the 68th St. Crib intake was always in the epilimnion (in the model). Such model behavior was consistent with temperature observations from the Crib. Since the hypolimnion never represented more than one-twelfth (8.33%) of the total depth in the Chicago-Calumet Harbor shoreline region, it was considered reasonable to neglect pollutant transport across the thermocline and, therefore, consider only single-layer dispersion in this preliminary effort.

The large (10.8km) grid spacing used limited the spatial resolution considerably.

Extensive model tests (Schwab and Katz 1974) indicated that diffusion, either actual diffusion or numerical "diffusion" resulting from the finite-difference model used, had little effect on pollutant-dispersion results in regions of strong currents such as the Chicago-Calumet Harbor shoreline.

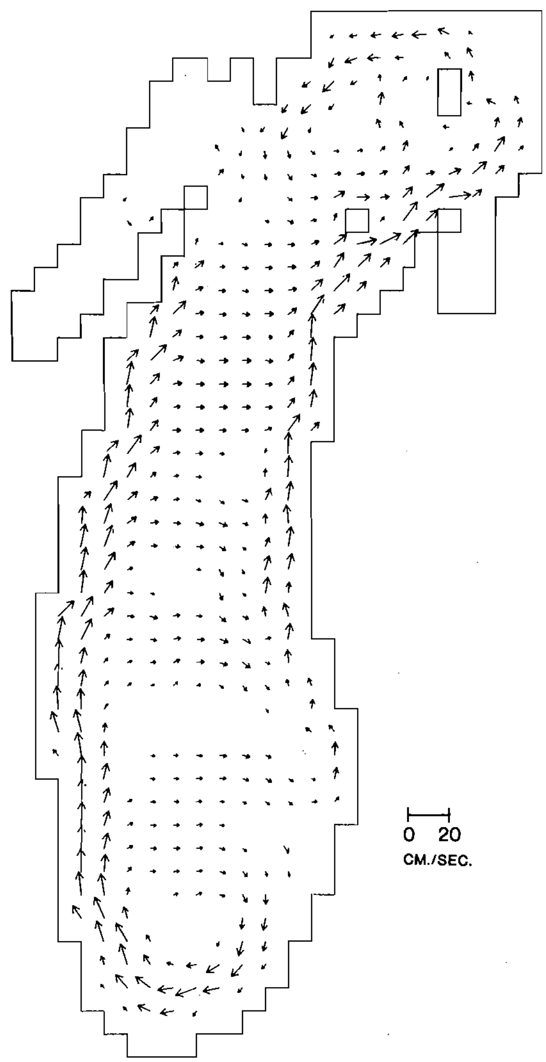


Figure 12. Simulated Lake Michigan steady-state summer velocity pattern (top-layer) for a south wind at 3.8m/sec.

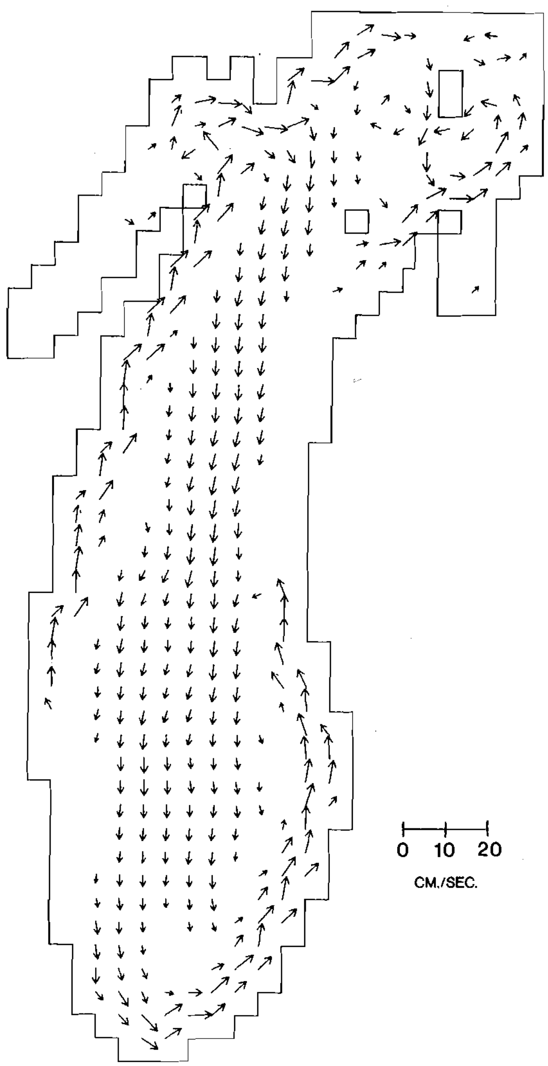


Figure 13. Simulated Lake Michigan steady-state summer velocity pattern (top-layer) for a west wind at 3.8m/sec.

Advection seems clearly to be the predominant horizontal transport mechanism in large lakes (Schwab and Katz 1974, Lick, Paul, and Sheng 1975, Bennett 1974b). Horizontal diffusivities are often treated as model parameters to be adjusted to provide smoothing in computational procedures (Lick, Paul, and Sheng 1975, Bennett 1974b). For the results shown here, a constant horizontal diffusivity of $10^5 cm^2/sec$ was used, largely for smoothing in regions of low velocity. A more realistic value for the 10.8km grid size would be $5 \times 10^5 cm^2/sec$ (Murthy, et al 1974), but, in some areas, numerical diffusion would still have a greater effect. Accurate treatment of nearshore horizontal diffusion, necessary in a more refined model but not attempted here, would require, at the outset, a much finer grid.

Because no data were available as to the "strength" and duration of actual storm discharges into Calumet Harbor, uniform pollutant slugs of arbitrary size (250,000 g/sec for 1 hour) were employed in the simulations described here. Model results were then scaled in a consistent manner to facilitate comparison with observations. This scaling, as described below, was not arbitrary. In the first episode simulation described, a scale factor was determined, establishing correspondence between observed ammonia levels and model results; this same scale factor was used for the results of the next two episode simulations. Such scaling, which resulted in treating all actual discharges as if they had the same "size", was used because of the lack of discharge observations. While not permitting close matching of model results with pollutant observations in the second and third cases, this scaling allowed a consistent determination of slug "arrival times" (defined below).

The timing of a slug's introduction in the model controlled the time of its appearance at the 68th St. Crib. In practice, because actual discharge times were not readily obtainable, slugs were introduced at the noon or midnight which best approximated the period of heaviest rain preceding a pollutant episode. This timing scheme was not intended to facilitate manipulation of the model to permit obtaining artificially improved agreement with observations, but was intended only to represent a reasonable "first guess" as to the timing of actual discharges into the lake.

Comparison of Model Results with Observations

This section presents model results for three pollutant episodes, along with observations of these episodes. Although simulated and observed data are plotted on the same axes for each episode, it is not intended that the reader should see great similarity between observed and computed curves. A conservative-pollutant model cannot effectively represent the overall behavior of highly bioreactive pollutants. Only transport is treated here, and the figures are intended to show its role in the episodes presented.

Figure 14 shows computed pollutant levels, observed NH_3-N and coliform data, and approximate wind and rainfall records, all corresponding to an episode in June, 1974. A slug was introduced, as shown, at the end of June 8, corresponding to 1.03 inches of rain that day.

For convenience in comparison, all three pollutant curves in this figure have been drawn with the same maximum height. The scaling required to match the computed curve with the observed ammonia curve was used to determine the scale factor, mentioned above, for all three episodes simulated. Thus, a concentration of 10^{-9} g/cm^3 in the model was associated with a measured ammonia level of 0.004 mg/l, for these episodes. This episode was chosen for setting the scale factor because of the large, easily compared peaks in both model and data during its first few days.

As shown in Figure 14, the model predicted the initial peak fairly well.

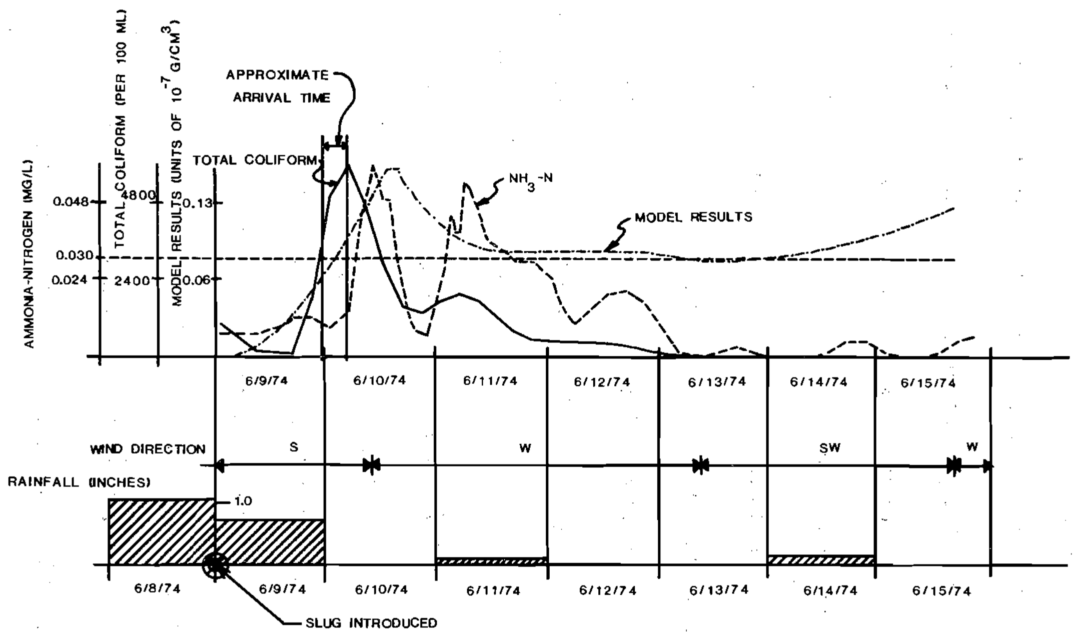


Figure 14. Computed and observed pollutant data for an episode in June, 1974, with wind and rainfall data.

In the model, this peak corresponds to an abrupt change of wind direction; the slug introduced spreads northward under a south wind and is then "pushed" back into Calumet Harbor by the action of a west wind. Since the model velocities are well within those actually observed (Snow 1974, Csanady 1967), this result indicates that, under changing winds, advection alone can cause great changes in concentrations within a few hours.

After a few days, the observed and computed data begin to diverge drastically; the conservative pollutant in the model stays in the area and moves northward again, causing increasing levels on June 14 and 15 after the real indicators appear to have decayed biologically. Figure 14, then, suggests the relative importance of transport and biological mechanisms during the episode. During the first few days, transport seems to predominate, thus controlling the onset of the episode.

The behavior of the pollutant "patch" is illustrated in Figures 15 and 16, which are model-generated concentration contour plots for June 10 and 13, respectively. Figure 15 shows the result of uniform wind-driven spreading along the shore, and Figure 16 shows the effect of a change in wind direction, as described above. Since the currents can change direction very rapidly as the wind changes (Snow 1974), very sharp peaks can be produced. A model with higher resolution could show much more of the fine detail of the observations.

"Arrival time", as shown in Figure 14, is defined as that time at which the computed concentration first reaches 0.075×10^{-7} g/cm^3, corresponding to an easily detectable ammonia level of 0.03 mg/l. In this simulation of an episode in June, the slug "arrived" about 26 hours after its introduction. The actual ammonia slug "arrived" (at the 0.03 mg/l level) about five hours later.

According to the conservative-pollutant model, the material introduced

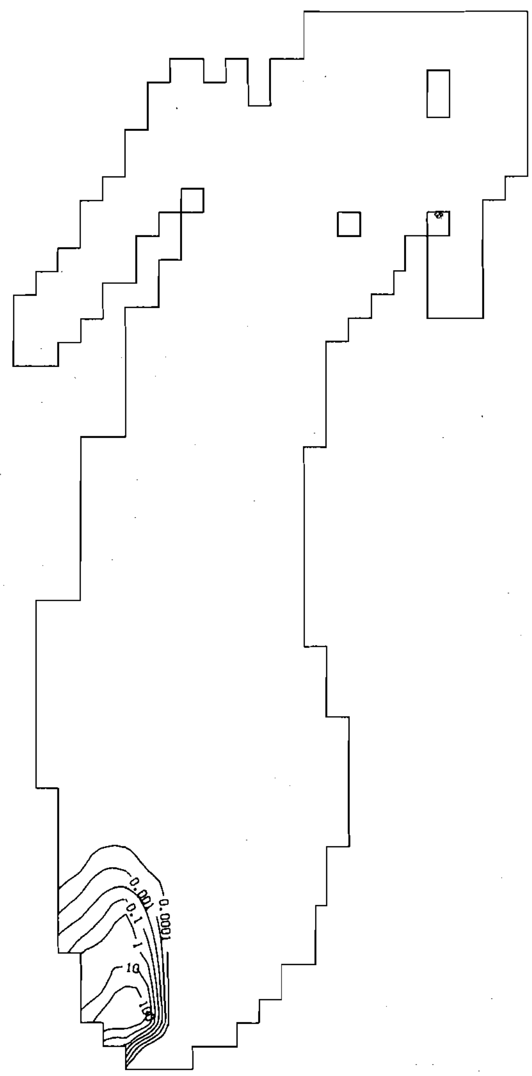


Figure 15. Simulated pollutant concentration contours for June 10, 1974 (units of 10^{-9}g/cm^3).

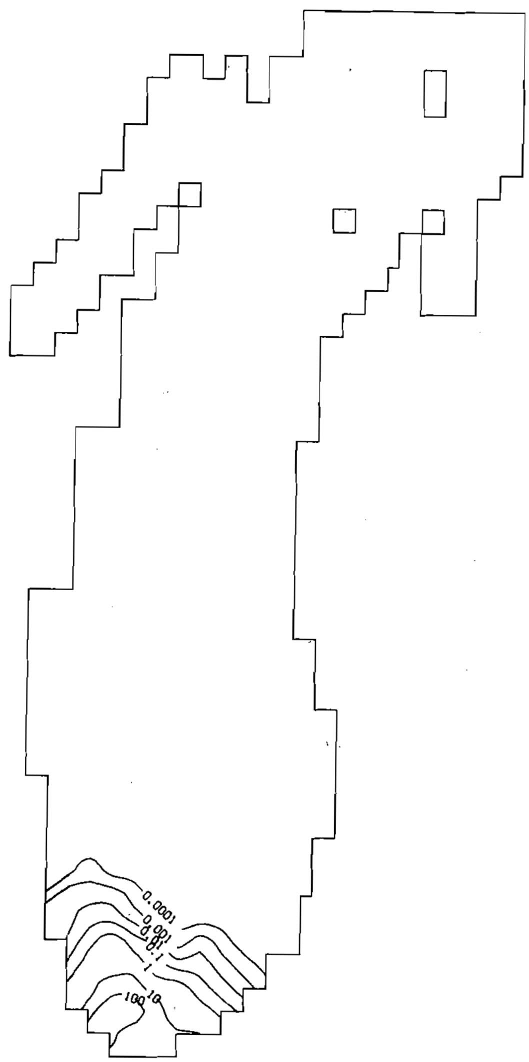


Figure 16. Simulated pollutant concentration contours for June 13, 1974 (units of $10^{-9} g/cm^3$).

remains around Calumet Harbor for the length of the episode; in the actual lake, the coliform bacteria die (Canale and Green 1972, Snow 1974) and the ammonia is taken up by nitrifying bacteria and converted to nitrites and nitrates (Sawyer and McCarty 1967). The by-products of ammonia decay, except insofar as they are precipitated, provide nutrients for biota in the area and might be expected to remain in the region, as indicated by the conservative-pollutant model. Thus, the hypothetical pollutant considered may be taken to represent both ammonia and its by-products.

No unusual pollutant concentrations were observed at the Central Filtration Plant during the period considered. The model indicated no Central Plant values greater than about 10% of the peak value indicated for the South Plant, even assuming no decay (thus assuming a gross overestimate of NH_3-N and coliform by the model); such values would be too small to be routinely noticed (cf. background levels). The edge of the pollutant patch never reaches the Central Plant in detectable amounts, in either the model or the real lake.

Figure 17 shows the same information as Figure 14, but for an episode in October, 1974; this episode corresponded to a period of almost steady winds, as shown. A slug was introduced at noon on October 29, corresponding to a 0.56-inch rainfall that day. The observed ammonia and coliform curves have been drawn so as to have the same maximum height on October 30. The computed curve has been scaled, as described above, so that a given concentration in the model corresponds to the same NH_3-N level as it did for Figure 14, for a determination of arrival time. The computed curve "arrives" about 38 hours after the slug's introduction, as compared with 26 hours in Figure 14, due to less favorable southwesterly winds on October 30. This curve climbs monotonically for the period shown, because flushing was not

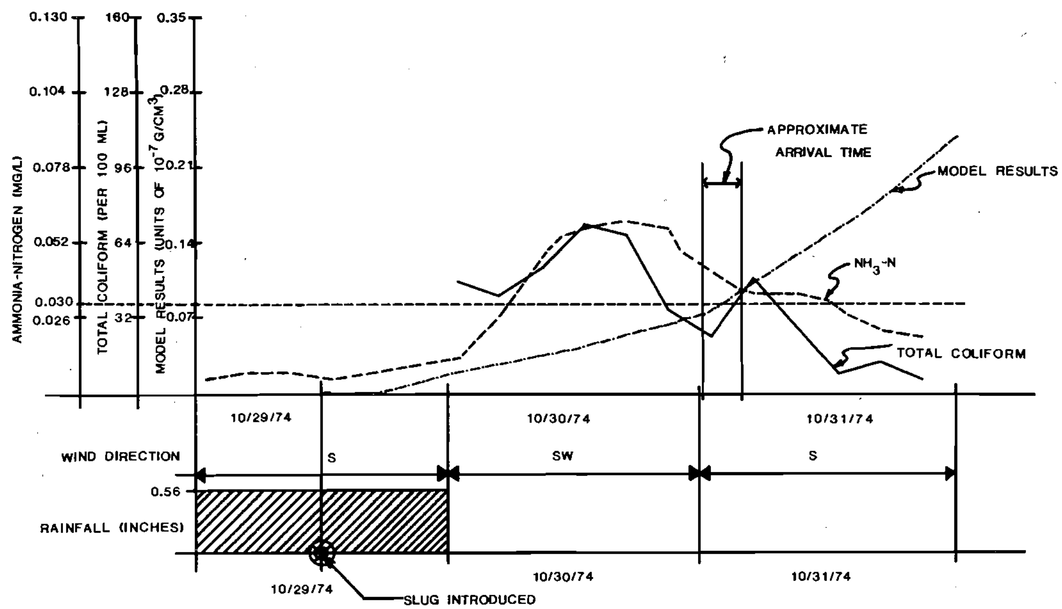


Figure 17. Computed and observed pollutant data for an episode in October, 1974, with wind and rainfall data.

effective within a three-day period; if the same currents had continued for a few more days, flushing would have begun to remove the slug from the area in the model. Once again, biological decay becomes predominant after a few days. As indicated by Figure 17 (time history) and by Figures 18 and 19 (contour plots for October 30 and 31, respectively), the conservative pollutant in the model spreads uniformly; the observed time history curves quickly flatten due to decay phenomena. The decay by-products here would tend to be spread much more effectively, away from Calumet Harbor, than in the previous example. Here, the model indicates a continuous transport of pollutant.

No unusually high levels were observed at the Central Plant in either the model or the real lake in this episode.

A third episode simulation is presented to indicate the potential use of a numerical model to determine the relative importance of different causative factors in a more complex situation. The ammonia-nitrogen curve in Figure 20 represents an observed "bad-water" period at the 68th St. Crib (see Figure 11) lasting from December 30, 1972 through January 7, 1973 (about 9 days); no unusual coliform levels were observed during this period. The highest ammonia levels were seen on January 1, about 2 days after a substantial rainfall, and on January 5, about 1 day after another storm; a reasonable first explanation for the observation, then, would be that two storm-discharge slugs were responsible. To test this assumption, two slugs were introduced in the model, as shown in Figure 20; these slugs were both of the same arbitrary "size" as those used in the single-slug simulations. As shown in Figure 20, the introduction of the first slug roughly accounts for the initial onset of the episode, but the second slug has little effect due to the prevailing winds following its introduction. Arrival time (about

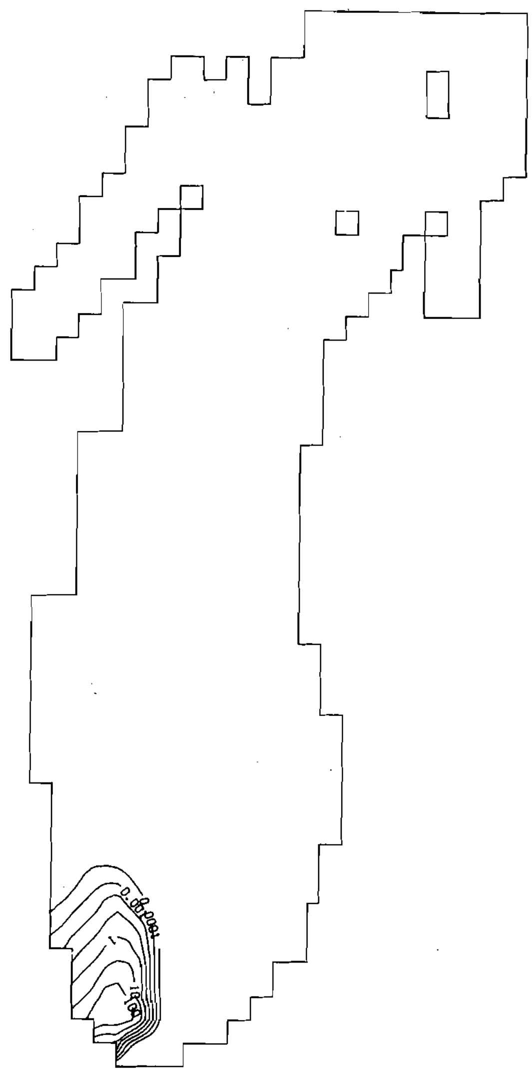


Figure 18. Simulated pollutant concentration contours for October 30, 1974 (units of 10^{-9} g/cm^3).

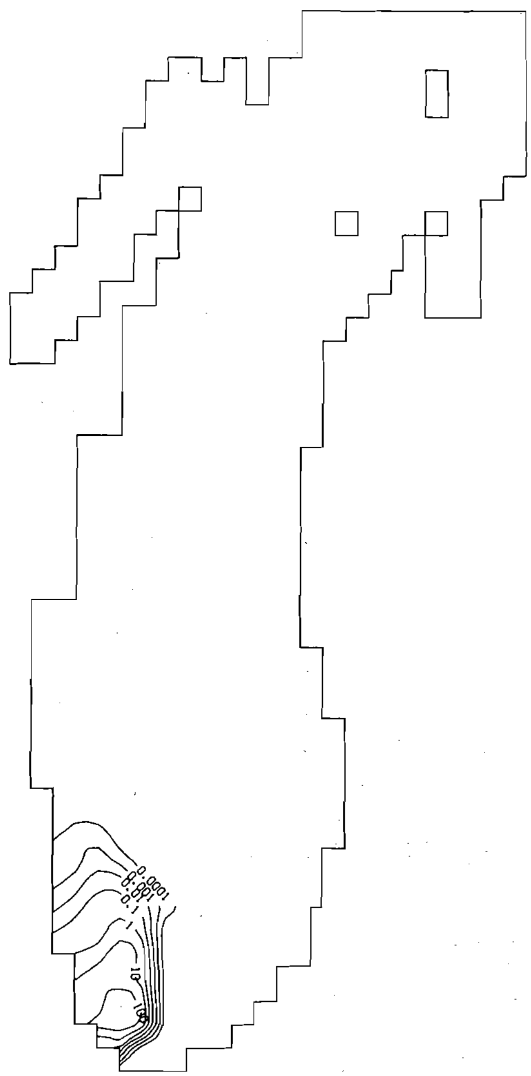


Figure 19. Simulated pollutant concentration contours for October 31, 1974 (units of $10^{-9} g/cm^3$).

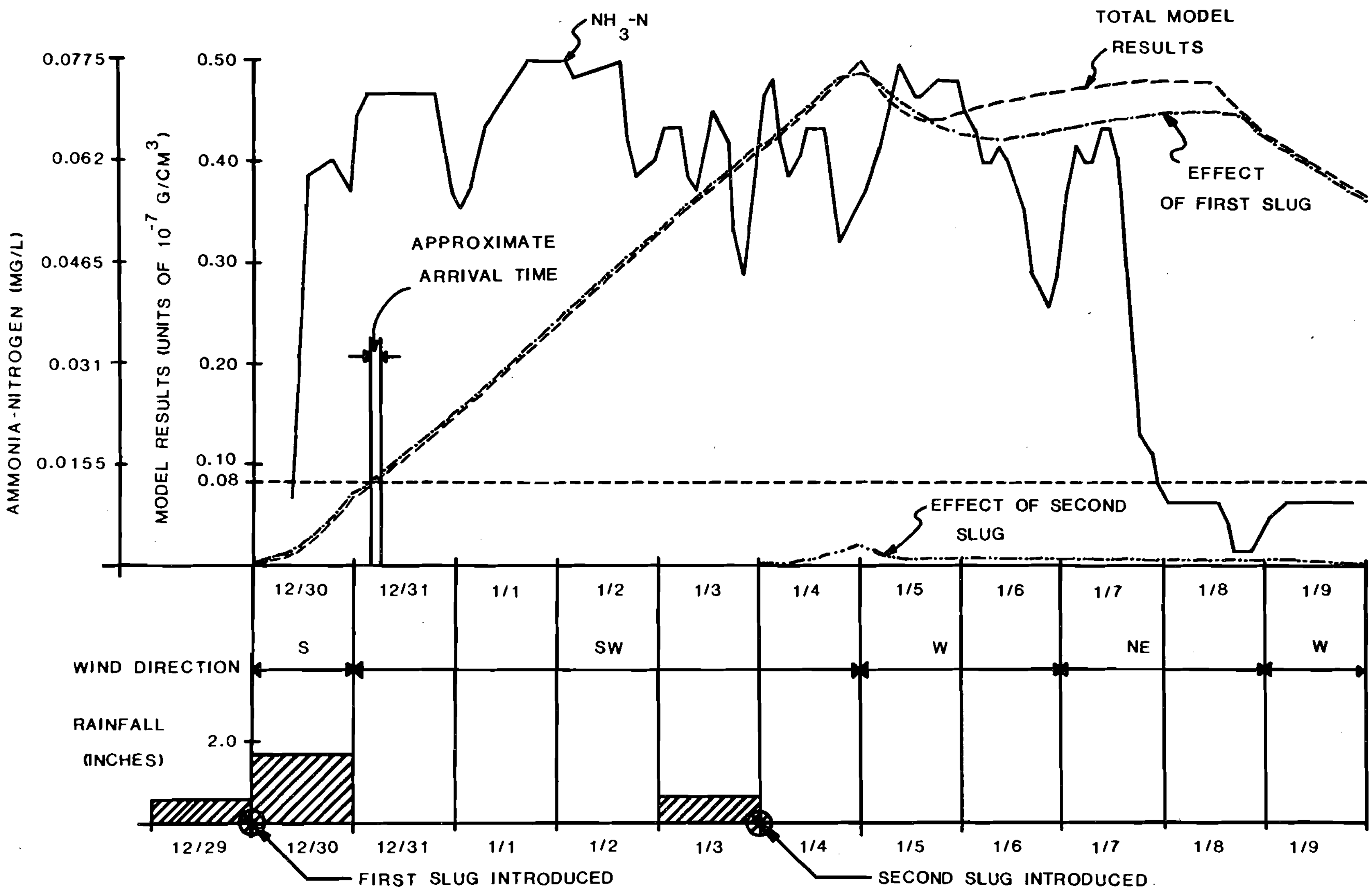


Figure 20. Computed and observed pollutant data for an episode in December, 1972 - January, 1973, with wind and rainfall data.

32 hours after the first slug's introduction) was determined as in the two cases described previously. Clearly, the observed rise in NH_3 - N levels on January 5 does not appear to be caused by a second storm discharge; this conclusion is obvious from the curves showing the effect of each individual slug. Therefore, it seems that both advective-transport and sediment-disturbance mechanisms are needed to explain this long episode. Another inference to be drawn is that, according to the model, different wind histories can cause grossly different pollutant levels to be seen after otherwise identical discharges (compare the two single-slug curves in Figure 20).

The sediment-disturbance explanation is reinforced by the absence of unusual coliform levels; coliform would not be expected to come from sediments. Central Plant pollutant levels remained low throughout the period considered.

Table 1 shows "arrival delays" in both observed data and model results for the three episodes described, where an arrival delay is defined as the interval between a slug's introduction <u>in the model</u> and either the appearance of an ammonia level of 0.03 mg/l in the observations or the slug's arrival time in the model. For the third episode, an arrival delay is given for only the first slug; the second slug never arrives, due to a wind change 24 hours after its introduction (see Figure 20). Table 1 suggests that the model's predictions of slug arrivals within 20-40 hours after a heavy rain near Calumet Harbor followed by winds having a strong southerly component are reasonable.

Table 1. Observed and computed arrival delays.

Episode Period	Observed Arrival Delay (hours)	Computed Arrival Delay (hours)
6/08/74 - 6/15/74	31	26
10/29/74 - 10/31/74	18	38
12/30/72 - 1/07/73	11	32

SUMMARY AND CONCLUSIONS

Types of Conclusions Obtained

Recent Lake Michigan studies here have led to two kinds of conclusions: conclusions about the behavior of pollutants discharged into important nearshore zones such as the Chicago-Calumet Harbor shoreline, and conclusions about the present state of the modeling art and its ability to simulate that behavior.

Conclusions Regarding the Fate of Calumet Harbor Discharges

1. As suggested by Figure 14, rapid changes in wind direction can cause large, rapid changes in nearshore pollutant levels. Thus, any transient water-quality changes in a region receiving an important time-varying discharge are highly dependent upon transport mechanisms. The importance of such transient changes is indicated by the high pollutant values measured during bad-water episodes at the 68th St. Crib; the onset of those episodes resulting from storm discharges seems to be governed largely by advective transport.

2. The model predicts greatly differing transport behavior in cases having changing and steady wind histories; the type of transport behavior predicted suggests one reasonable explanation for differences in the observed data and suggests an hypothesis regarding the immediate fate of Calumet Harbor discharges. Under steady winds, discharged pollutants disperse uniformly and slug discharges, if they do not decay rapidly, are probably flushed away from their sources. Under varying winds, discharges show a tendency to stay near their sources, and the movement of "edges" of pollutant patches can cause great changes in levels in a few hours; abrupt changes in level seem to correspond to abrupt wind changes. Pollutants such as coliform and

ammonia-nitrogen which decay quite quickly seem to stay in the Calumet Harbor area until they decay because, under any usual wind conditions, flushing occurs more slowly than decay.

The lack of episode data from the Central Filtration Plant (about 14.5km north of the South Plant) is completely consistent with the hypothesis that most of the observed pollutant changes form while still in the Calumet Harbor-South Filtration Plant area. Both the model and the measurements suggest that very little pollutant is transported as far north as the Central Plant intake, compared with that delivered to the 68th St. Crib. The type of episode data seen at the South Plant would probably be seen at the Central Plant if the amounts delivered were above measurement thresholds.

3. The by-products of the pollutants observed might behave, insofar as transports are concerned, in much the same manner as the conservative pollutant considered here; the indicators observed (e.g., $NH_3 - N$, coliform) may not reveal the time extent of buildups under "worst case" conditions.

Conclusions Regarding the Modeling of Nearshore Dispersion Episodes

1. Two circulation and pollutant-dispersion models have been developed for Lake Michigan. The two-layer model (Kizlauskas and Katz 1973, 1974, Schwab and Katz 1974, Katz and Schwab 1975) provides a fairly economical means of simulating large-scale transport phenomena where high spatial and temporal resolution and great vertical detail are not required. The modified Simons model provides, in its present form, an added capability of treating large-scale phenomena with considerable detail in the vertical and allows the consideration of baroclinic effects.

These coarse-grid models are directly applicable to the study of lake-wide processes; verification and calibration of such whole-lake models for Lake Michigan would necessarily be a very large and costly undertaking.

Thus, while such simulations can provide many insights into the behavior of the lake, making them predictive of actual observations without an elaborate whole-lake data base would be quite difficult. The use of local high-resolution models to treat local currents and dispersion episodes, requiring far less data for calibration and verification, seems to offer an improved means of studying the effects of important effluent outfalls.

One goal of the preliminary episode simulations presented here was the determination of some of the requirements for a nearshore model; other requirements have been determined from the observed nature of lake currents. Several existing "state-of-the-art" models have been evaluated as regards these requirements (see Appendices A and B).

2. The results shown here estimate the relative importance of transport and biological mechanisms in modeling ammonia and coliform episodes observed. It seems clear that such episodes cannot be modeled accurately without considering both kinds of mechanisms.

3. In a limited area such as Calumet Harbor, empirical coefficients for the decay of indicators observed might be determined, as a simple means of introducing biological effects into a model. Such a non-mechanistic model would necessarily need to be made dependent upon a number of time-varying parameters such as temperature and pH and the initial biological state of the nearby lake waters (before a discharge). Such an empirical model would be severely limited in application. Its validity would exist only for the particular locale considered, but in some circumstances, with a sufficient data base, it might provide some predictive capability. For predictive applications involving episodes unlike those already observed, an episode model would require a realistic, mechanistic biological model as one of its components.

4. The low background levels observed at both filtration plants indicate that pollutant episodes can be modeled, especially for effluent discharge monitoring and control purposes, without detailed knowledge of initial concentrations. Recent water intake data indicates no episodes apparently caused by pollutants entering the Chicago area from the north. The indicators seen ($NH_3 - N$ and coliform) decay rapidly compared with the time (at least a week) required for advective transport from distant sources. Thus, apparently, only local sources (including, of course, the lake bottom) need be considered in modeling the transient episodes observed, and in monitoring efforts related to such models. Specifically, it seems very reasonable to assume that ammonia and coliform discharged outside the Chicago-Calumet Harbor area would decay to sub-background levels before reaching that area in measurable amounts. In any simulation of the long-term buildup of longer-lived pollutants, however, consideration of distant sources would be necessary.

5. It seems clear, then, that the type of "bad water" episodes observed, representing the highest pollutant levels seen in the area, may be modeled quite efficiently with a model having very high resolution in only the area of immediate interest and including only local sources, provided such a model can be calibrated with data on the same scale. For specialized purposes, a conservative-pollutant episode model, with simple decay mechanisms for non-conservative substances, might provide sufficient insight and predictive capacity for water-quality management pruposes. By indicating the likely patterns of dispersion from a given source, such a model might be of great use in planning surveillance activities such as current and water-quality measurement programs.

6. A detailed nearshore episode model [including vertical transports (e.g., Simons 1972, 1973a, Leendertse, et al 1973, Bennett 1974b, Lick, Paul, and

Sheng 1975, Sheng and Lick 1975) and transport from bottom sediments (e.g., Moore and Silver 1973)] would contribute to understanding more complex processes in the Great Lakes. In an aquatic ecosystem simulation, it would provide a means of describing nutrient transport from shore sources (rivers, canals, industrial plumes, harbor mouths, etc.) to the open waters of the lake, thus providing a link between existing source (stream, plume, estuary) models and whole lake models. Such nearshore transport mechanisms, between zones with greatly differing depth, light, and/or temperature regimes, can only be guessed in many cases from existing Lake Michigan experimental studies (e.g., Snow 1974). In addition, a nearshore model would be valuable in studying nearshore currents themselves, especially as related to existing and proposed lakefront development (e.g., the Lakefront Plan of Chicago 1972).

It has been determined (Appendix B) that developing a high-resolution, multiple-grid-spacing version of the Simons model, with more elaborate treatment of model parameter variations, offers a direct, attractive means of performing practical nearshore simulations; development of such a model is in progress.

7. For this or any other episode model to be of great use, verification would necessarily be required. Meaningful verification would require frequent or continuous monitoring of effluent discharges and their effects over a period of months. Continuous measurements, presently unavailable for such sources as the Indiana Harbor Canal, offer the only means of gauging actual transient pollutant loadings of Lake Michigan. Infrequent measurements can miss effluent "slugs" discharged, thus grossly underestimating loadings and making verification of any model difficult (if not impossible).

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APPENDIX A
REQUIREMENTS FOR A NEARSHORE MODEL

Most obviously, a nearshore circulation model must have high spatial and temporal resolution if it is to simulate complex transient behavior. Strong coastal currents less than 1 km wide have been observed in Lake Ontario (Csanady and Scott 1974), for example. Simply using a finer grid and smaller time-steps, however, probably will not allow existing models to represent nearshore behavior well. Nonlinear effects thought to be observed nearshore (Csanady 1972, 1974) are unimportant in large-scale models (due to low Rossby numbers (Simons 1972, 1973a, 1974, Bennett 1974a)); these convective momentum transports must be included carefully in nearshore models. Changes in apparent eddy viscosities and diffusivities (especially in the vertical) have great effects on internal model behavior (Simons 1973b, 1974, Bennett 1974a, b); the simple empirical relationships used for such quantities cannot represent local changes in these parameters accurately. Although the entire concept of representing small-scale turbulence by apparent diffusivities and viscosities is inherently incorrect (Neumann and Pierson 1966), slightly more elaborate empirical formulations, perhaps employing a three-dimensional "mixing-length" formulation (Boericke and Hall 1974, Goldstein 1938) might allow more realistic treatment of observed turbulent behavior. Since realistically-varying viscosities and diffusivities should be used, and since transient behavior is of great importance, a numerical model should be capable of running without the imposition of an artificial horizontal viscosity for "smoothing" of numerical anomalies. Even more important than eddy-dispersion parameters, the wind and bottom stresses, which largely govern overall vertically-integrated transports, should be formulated realistically. Quadratic stress laws commonly used (Simons 1972, 1973a, Bennett 1974a, b, Haq, Lick, and Sheng 1974, Wilson 1960) are clearly incapable of representing energy transfer at boundaries correctly (Bennett 1975) when constant coefficients are used. More accurate representations of these stresses, probably empirical relations (e.g., Hsu 1974), should be incorporated.

Many models for nearshore behavior in idealized basins have been developed (e.g., Birchfield 1972, 1973, Blumsack 1972, Csanady 1974, Csanady and Scott 1974, Bennett 1974a, Pedlosky 1974). While these models cannot accurately represent conditions in actual lakes, they can provide much insight into the relative importance of various processes in determining nearshore circulations. Baroclinic effects are clearly important (e.g., Csanady and Scott 1974); temperature changes and their resulting density fields must be included in any general nearshore model. Wind set-up and its resulting flow must also be considered (Haq, Lick, and Sheng 1974); a nearshore model should include the whole lake, although without high resolution outside of areas of particular interest.

Local river and stream inputs should be treated accurately in a nearshore model to be used for pollutant-dispersion studies. The role of buoyant or sinking plumes in establishing the vertical distribution of a substance near its source can be very important (Lick, Paul, and Sheng 1975, Snow 1974).

Spatially-detailed fields of wind and surface pressure will probably be required for accurate nearshore simulations, and especially for the simulation of storm-driven episodes. Nearly uniform wind fields which often are satisfactory for large-scale studies (J.R. Bennett, personal communication), are probably of little value for localized studies.

In shallow nearshore zones, bottom topography can have large effects on the entire circulation; accurate, finely-spaced bottom data would be essential to any successful nearshore modeling attempt.

APPENDIX B
EXISTING THREE-DIMENSIONAL MODELING CAPABILITIES

The equations governing the motions of a large fresh-water lake may be written (given the customary hydrostatic and Boussinesq approximations) as follows:

1. A vector momentum equation to be solved for horizontal velocity components.
2. An equation of mass conservation, which may be solved for vertical velocities and free-surface displacements.
3. A heat-transport equation which may be solved for a temperature distribution in space.
4. An equation of state relating temperature and density (usually a quadratic approximation).

These basic equations may be solved in many ways, and each method of solution has its own advantages and drawbacks in any given application. Some existing "state-of-the-art" models representing a variety of methods will be described here and discussed in relation to their applicability to transient nearshore phenomena.

The Leendertse-Alexander-Liu Model

One of the simplest and most straightforward three-dimensional hydrodynamic models in use is that developed by J.J. Leendertse, R.C. Alexander, and S.K. Liu of Rand Corporation (Leendertse, et al 1973). In this model, a basin is divided vertically into a number of layers with rigid, permeable boundaries (except at the free surface), and the equations applicable are vertically integrated within each layer. The model includes horizontal and vertical diffusion and advection of momentum and salinity (as published, this model considers density variations due to salinity only; for application to a body of fresh water, salinity could simply be replaced by temperature and the equation of state changed). Within each layer, a single Richardson lattice is used (only the normal horizontal velocity component at each side of each rectangular cell is computed; vertical velocities, surface displacements, and salinity are computed at cell centers, as viewed from above). The absence of two Cartesian velocity components at each "velocity point" in the horizontal necessitates considerable interpolation in evaluation of Coriolis and momentum-advection terms. The model is completely explicit, with "leapfrog" centered time-differences used for all but the diffusion terms, which are foward-differenced for stability. The direct inclusion of the free surface in this model makes the maximum allowable time-step very small for stability. The small time-step required is this model's greatest drawback.

Constant horizontal eddy viscosities and diffusivities are used; vertical momentum transfer by diffusion is made proportional to quadratic expressions for inter-layer stresses. Quadratic wind-stress and bottom-friction laws are imposed, as is a no-slip condition at the sides of each layer.

As described in the published report cited, this model does not allow for layers with non-constant depths; in this form, the model cannot treat a realistic lake bottom.

The use of centered time-differences here requires that two time-levels of variables must be stored at all times, almost doubling the storage required by some other schemes which are also stable (e.g., Platzman 1972).

The time-differencing method used here is stable if the Coriolis terms are not included; these terms might cause the appearance of spurious computational modes if no viscosity is introduced (J.R. Bennett, personal communication).

This model has been tested by comparison with an analytical solution for a rectangular basin and by spectral techniques, and appears to represent the theoretical dynamics well in idealized cases. Tests have also been run with a "Lake Michigan-like" closed basin.

The model considered here has some attractive features for nearshore adaptations; all of the nonlinear terms are included, and the single Richardson lattices used would simplify treatment of boundaries (especially between grids of different sizes). The lack of efficiency caused by the perhaps overly direct numerical approach is the greatest apparent defect in this model, apart from the obvious (and probably easily remedied) inability to resolve realistic bottom topography.

The Simons Model

The circulation model developed by T.J. Simons at the Canada Centre for Inland Waters (Simons 1972, 1973a, b, 1974) is a free-surface model which avoids much of the computational expense imposed by the free surface in the Leendertse-Alexander-Liu model. Computational efficiency is obtained by elimination of free-surface terms from the equations for internal flow. Vertical structure is again incorporated by dividing a lake into a number of layers with rigid, permeable boundaries, with vertically-integrated equations applied within each layer. However, instead of directly solving the layer momentum equations for layer transports, Simons reformulated these equations into one equation for the total integrated transports in the lake and a set of shear-flow equations for the velocity differences between the layer midpoints. Forming the shear-flow equations removes the surface-pressure-gradient terms from the internal-flow computations. The free surface is allowed to act on the internal flow, however, because the total transports generated by the vertically-integrated calculations are used in updating the internal flow. The internal flow is also used in updating the integrated transports. Thus, only the overall transports need be calculated using a short time-step, and a much larger time step like that allowed in a rigid-lid model may be used for all other computations.

Overall integrated transports and internal velocity shears are converted into individual layer transports at each internal (long) time-step. These transports are then used to predict the advection of temperature and re-converted to overall transports and velocity shears. The computations required to repeatedly convert overall transports and shear flows to layer transports and back again are fairly costly in computer time.

The vertically-integrated transports computed represent the barotropic component of a lake's circulation; the internal computations represent mainly the baroclinic component (Charney 1955, quoted by Simons 1973a, 1974).

In the horizontal, computations are performed on two overlapping Richardson lattices rotated 45 degrees with respect to a third lattice used for diffusion. This arrangement, while it complicates the treatment of boundaries, allows the computation of two components of velocity at each horizontal "velocity point". Thus, the Coriolis terms may be evaluated directly without space interpolation, eliminating possible computational modes associated with space-averaging (J.R. Bennett, personal communication) without the introduction of an artificial viscosity. An artificial horizontal viscosity <u>is</u> required, however, to prevent "grid dispersion" (divergence in time of the solutions for the two overlapping velocity lattices) in the existing form of the model.

Horizontal and vertical diffusion of momentum and temperature are included; advection of momentum is neglected, due to its relative unimportance on the large scales considered. Horizontal and vertical advection of temperature are simulated.

The momentum equations are time-differenced in such a way that new velocity values replace old values as soon as they are determined; this method, while stable, requires the storage of only one set of values for each variable. Forward differences are used for diffusive-friction terms, and a Lax-Wendroff scheme is used for temperature advection, for stability.

Quadratic bottom-and-wind-stress formulations are used. Constant horizontal viscosities and diffusivities are used throughout; vertical diffusivities are related to time-averaged wind stresses and static thermal stability.

Each layer may have a varying depth; realistic bottom topography may be treated directly and easily.

The Simons model was originally developed for use with data taken on Lake Ontario during the International Field Year for the Great Lakes (IFYGL); it has been extensively compared with such data, and has been verified quite successfully for most of the year (Simons 1973b, 1974). During episodes in which large-scale shore-bound waves are predominant (Csanady and Scott 1974), this model exhibits excessive damping, perhaps partly because of excessive horizontal viscosity, and partly because of insufficient nearshore resolution (Bennett 1975). No other model has been the subject of such intensive comparison with observations, and much has been learned about calibrating this model for different applications.

The Simons model has been used successfully in long-term large-scale conservative-pollutant dispersion studies on Lake Erie (Lam and Simons 1974, Lam, Jaquet, and Burns 1975).

The Simons model has a number of advantages for nearshore adaptation; the free surface is included efficiently and the multiple lattices used would facilitate the inclusion of momentum advection terms. These lattices would, however, complicate the matching of coarse and fine grids in a multiple-grid-size model. The use of 45-degree-rotated lattices might, however, allow the easy treatment of diagonal boundaries.

The Bennett Model

The Simons model was developed as part of the Canadian contribution to the IFYGL effort; its U.S. counterpart was developed by J.R. Bennett, then with NOAA. The Bennett model (Bennett 1974b, 1975) is a rigid-lid model using a vorticity equation for the vertically-integrated circulation to treat the effects of surface pressure.

Vertically-integrated layer equations are not used; three-dimensional equations are solved directly for velocity and temperature fields. A vorticity equation obtained from the (scalar) momentum equations is used to obtain a stream function for the vertically-integrated flow, and this stream function is used to correct preliminary predictions of internal velocities at each time-step to ensure truly non-divergent flow.

At each vertical level, a single Richardson lattice is used. Again, this approach makes treatment of boundaries simple while necessitating space-interpolation in evaluation of Coriolis and momentum-advection terms.

Time-differencing of the horizontal momentum equations is accomplished through an explicit scheme which involves immediate replacement of old values by new values as soon as they are determined, thus reducing the storage requirements. This differencing scheme is similar to the scheme described by Platzman (1972). Temperature advection is treated with an Adams-Bashforth (Haltiner 1971, Carnahan, et al 1969) scheme (requiring the storage of temperature fields at two time-levels) and vertical temperature diffusion is treated using forward time-differences. The elliptic vorticity equation is solved by using DuFort-Frankel over-relaxation (Carnahan, et al 1969).

Quadratic bottom-and-wind-stress formulations are used, with constant coefficients. A constant, fairly high horizontal eddy viscosity is used; this viscosity is required to suppress computational modes arising from the four-point velocity averages used to evaluate Coriolis terms. Vertical viscosities and diffusivities are related empirically to local wind stresses and Richardson numbers (and, thus, to static thermal stability and velocity shear).

Nonlinear momentum-advection terms are not presently included because they were found to be negligible in a large-scale Lake Ontario model; horizontal temperature diffusion is similarly neglected. The terms omitted could be added in a straightforward manner similar to that of Leendertse, et al (1973), who used a similar lattice structure.

Realistic bottom topography may be included directly.

Surface displacements may be obtained from the vorticity calculations performed.

The Bennett model has been compared with IFYGL observations and with the Simons model. Except for realistic treatment of free-surface dynamics, the Bennett model produces results essentially equivalent to Simons' (Bennett 1975) and can provide much better vertical resolution (more levels) than Simons' model, using far less computer time (due to rigid-lid simplifications). This model exhibits similar defects in reproducing certain wave motions as does Simons' (Bennett 1975); tests using a finer grid are being run to determine the importance of grid size in this problem.

The Bennett model seems to be one of the best, computationally, for simulating long-term lake-wide motions economically.

For nearshore applications, however, Bennett's model is greatly limited by its rigid-lid formulation. The need for an artificially high viscosity to suppress computational modes would also have to be eliminated.

The Case Western Reserve Models

A number of interesting models have been developed by individuals working with W.J. Lick in the Department of Earth Sciences, Case Western Reserve University. Included are models with variable and constant densities, free surfaces and rigid lids, and multiple grid sizes (Lick, Paul, and Sheng 1975, Sheng and Lick 1975, Haq, Lick and Sheng 1974, Paul and Lick 1973, 1974), which have been applied mostly to Lake Erie. The variable-density models have rigid lids; two which have been applied to nearshore boundary regions will be considered here.

Y.P. Sheng has studied nearshore currents and the dispersion of settling and non-settling materials in Cleveland Harbor (Sheng and Lick 1975). While the results presented to date have concerned steady-state circulations, especially as related to proposed offshore construction, the model itself allows the treatment of time-varying nearshore processes on a set of rectangular grids with varied internal spacings. All nonlinear terms have been included and stability testing has been performed (Y.P. Sheng, personal communication).

J.F. Paul has developed and verified a model for thermal and river discharges into large bodies of water (Paul and Lick 1973, 1974); this has been expanded into a variable-grid-spacing whole-lake model with high resolution near shore (J.F. Paul, personal communication). This model, which allows for special treatment of river and harbor mouths, has also been used mostly for steady-state simulations, although it, too, is basically a time-varying model. A version of this model is being used for whole-lake studies of Lake Erie by R.T. Gedney at NASA's Lewis Research Center in Cleveland.

The Sheng and Paul models are similar in most important numerical details. They are both three-dimensional models with "stretched" co-ordinates in the vertical such that the same number of layers is present at each horizontal grid point, with resulting greater resolution in shallow water. Surface pressure is treated by forming a vertically-integrated Poisson equation. The pressures obtained from this equation can, of course, be easily converted to equivalent free-surface displacements. The Paul model incorporates uniformly changing grid spacing near discharges; this feature is computationally costly.

Very little verification exists for the Case Western Reserve models as lake models, although the Paul model has been verified substantially for thermal plumes (Lick, Paul, and Sheng 1975). Comparisons with actual data from Cleveland Harbor were scheduled for the summer of 1975 (W.J. Lick and J.F. Paul, personal communication). Throughout, however, little emphasis has been placed on short-term transient-episode behavior.

In general, then, while the Sheng and Paul models provide very high resolution near shore and include all nonlinear advective terms, the assumption of a rigid lid limits their usefulness for studies of transient behavior (Haq, Lick, and Sheng 1974). The use of somewhat irregular co-ordinates results in increased computational expense and truncation errors. In a simulation of nearshore currents, the shape of "coastal jets" in a model might tend to follow patterns of spatially-changing resolution.

Summary

Among existing lake models, free-surface models seem to have the greatest potential for accurately representing transient characteristics of lake dynamics and should be used where short-term responses to wind-stress impulses are to be simulated accurately. Rigid-lid models seem useful largely for treating long-term phenomena such as lake-wide advective pollutant transports; for effects with sufficiently long time scales on which transient effects are unimportant, these models offer tremendous savings in computer time.

All the existing models considered here seem to produce similar results under similar conditions; they most likely all have some of the same problems in resolving lake-wide nearshore wave motions. Each has features which suggest its use for certain specialized applications.

For the purpose considered here, the development of a nearshore model, the Simons model seems to offer the greatest likelihood of success. This model includes, or can be easily made to include, all the phenomena of greatest interest, while still being more efficient than a simpler model (such as the Leendertse-Alexander-Liu model). Also, the Simons model has been compared extensively with data, and calibration of a nearshore version might be simplified by use of existing empirical techniques.